EFFECTS OF *ZAI* PIT TECHNOLOGY (*Tumbukiza*) ON SOIL MOISTURE CONSERVATION FOR COWPEA *(Vigna unguiculata* L. Walp.*)* PRODUCTION IN DRYLAND AREAS OF KENYA

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A Thesis Submitted to the Graduate School in Partial Fulfillment of the Requirements for the Master of Science Degree in Soil Science of Egerton University

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DECLARATION AND RECOMMENDATION

Declaration

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Recommendation

This Thesis has been prepared with our supervision and submitted for examination with approval and recommendation as the university supervisors.



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DEDICATION

This work is dedicated to my lovely daughter Blessing Venney Eyra, for enduring my weekly absence during field work and data collection, my dad George Oduor for always encouraging me that I am destined for greatness and any other person who strive daily to achieve food security.

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ABSTRACT

Zai pit technology (*Tumbukiza*) is a water harvesting technique that uses micro pits dug in the farms to collect water to support plants throughout the growing season. In this study, *Zai* pits were used in two ASAL locations in Kenya, to grow cowpeas (*Vigna unguiculata* L.) as the test crop, with the main aim of determining the combined effect of *Zai* pit technology and manure on selected soil properties, growth and yield of cowpea; to determine the effect of *Zai* pit technology on soil moisture dynamics and water use efficiency (WUE) of cowpea (*Vigna unguiculata* L. Walp) in ASAL localities; and lastly, to assess gross margin of using *Zai* pit technology for soil moisture conservation in cowpea production. RCBD layout in split – plot arrangement was used, where Cow manure was the main plot factor while subplot factors were the various *Zai* pit depths of 30 cm (Z_{30}), 45 cm (Z_{45}), 60 cm (Z_{60}) and flat fields (Z_0), that is, plots without the technology to act as control (farmer practice). Data was analysed using Statistical Analysis software (SAS), version 9.2 and means separated using Tukey's Honestly Significant Difference (HSD). Inorganic nitrogen (N_{in}), and extractable phosphorus (P_{ex}). Varied significantly ($P \leq 0.05$) with Zai depth, with Z_{45} having highest N_{in} at 1.17 against the least, at 0.89 mg kg^{-1} in the Z_0, while P_{ex} was highest in Z_{30} at 102.3 mg kg^{-1} while Z_0 having the least P_{ex} of 89.7 $mgkg^{-1}$. Soil moisture (v/v), evaluated weekly, increased to 375% in Naivasha and 418% in Katumani cumulatively. Manure brought significant effect to the plant height, highest at 32.9 cm and stem diameter of cowpea, largest at 0.51 cm. Water use efficiency (WUE) was significantly ($P \leq 0.05$) different across *Zai* treatments with Z_{45} having the highest of 14.51 kg $Ha^{-1}mm^{-1}$ while flat plots (Z_0) producing least of 7.76 $KgHa^{-1}mm^{-1}$. Similarly, gross margin was varied significantly across *Zai* treatments, with Z_{45} performing better, yielding KES. 57,167 per hectare, against KES 9,245 per Ha from flat plots in Naivasha while in Katumani, Z60 producing the highest GM of KES 48740 per Ha while flat farms making a loss of KES 3067 per Ha. The study revealed that *Zai* pit technology improves soil environmental conditions hence higher grain yields from *Zai* pitted plots, with Z_{45} yielding 853.33 $kg.Ha^{-1}$ against 685.0 $kg.Ha^{-1}$ in Flat plots in Katumani while 931.66 $kg.Ha^{-1}$ in Z_{45} against 563.33 $kg.Ha^{-1}$ from Flat plots in Naivasha. From this study, use of *Zai* pits enhances yields, WUE and is profitable for cowpea production in AEZ IV. Further studies in other AEZs and with other crops should be conducted to generate recommendations for scaling out the use of this technology.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	–	Agro – Ecological Zone
ASAL	–	Arid and Semi-Arid lands
AWC	–	Available water content
DAP.	–	Days After Planting
ECOSTAT	–	Department of Economics and Statistics, Kerala, India
EPHTFCP	–	Eastern Province Horticulture and Traditional Food Project
FAO	–	Food and Agriculture Organisation of the United Nation
FC	–	Field Capacity
FYM.	–	Farmyard Manure
GLCPA	–	Green-life Crop Protection Africa
GM	–	Gross Margin
GPS	–	Global Positioning System
IFAD	–	International Fund for Agricultural Development
KALRO.	–	Kenya Livestock and Agriculture Research Organisation
NAAIAP	–.	National Accelerated Agricultural Inputs Access Programme
PWP	–	Permanent Wilting Point
SAS	–	Statistical Analysis Software
SQPTL	–	Soil Quality Pty Limited
TR	–	Total Revenue
TVC	–	Total Variable Cost
WUE	–	Water Use Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Drought is a major hindrance to crop production in most parts of the world (Kebede *et al.*, 2018). According to Kenya Development Plant Vision 2030, 80% of the Kenyan land is classified under Arid and semi-arid lands (Mwenzwa & Misati, 2014; Njoka *et al.*, 2016). Considering political boundaries, 29 out of the 47 counties in Kenya are ASALs. Among these counties are specific locations, for instance, whole of Machakos county and Lare and Naivasha sub–counties in Nakuru county.

Communities living in these locations within the counties are faced with the challenges of water supply. Agriculture, being a function of water, is affected greatly since water is needed for the entire life cycle of the plant, from the early stages of planting to help in the moistening of the seeds for germination, to availing plant nutrients for uptake and finally to the growth and development of the plant. Soil moisture also affects land productivity. The amount of water contained in a unit mass of soil is the most influential factor that affects the growth and development of the plants (Kebede *et al.*, 2018).

Various methods have been used to conserve soil moisture content and reduce water loss in the ASAL areas, including the use of artificial mulching material. Some of these mulches like plastic mulches are non-biodegradable, thereby leading to soil/environmental pollution. Some of the biodegradable ones are quite expensive since they get decomposed after one growing season, prompting the farmer to purchase them after each and every growing season. Tied ridges has also been used as a water harvesting technique (Denison *et al.*, 2011) in the farms. It has been successful, but only in farms with less than two percent (<2%) slope (Silungwe *et al.*, 2019). Tied ridges also reduces the crop population as the plants are only grown on the two opposite sides of the ridge, compared to *Zai* pits, whose number of plants per pit depends on the crop to be grown as well as the size of the pits being used.

Zai pit technology is the use of holes dug in the farm for planting crops to help in soil moisture retention and nutrient/fertilizer maintenance. It is a water harvesting technology (Partey *et al.*, 2018) that is suitable for areas with unpredictable rainfall and subsequent crop failure. The rain water that would otherwise be lost through runoff are collected in the pits, hence stay longer and are utilized slowly by the plants for various physical, biological and chemical processes (Kimaru - Muchai *et al.*, 2017). This helps in the reclamation of the drought stricken Arid and Semi-Arid Lands (ASAL) back to their originally productive status. It also helps in reducing waste of fertilizer and manure, and increase their efficiency since instead of

being applied in the whole field, the manure is only applied in the pits in which the crops are to be grown. The manure, or any soil treatment, is mixed with the upper 50% of the soil, which is then returned back to the soil (***Figure 1***), while the lower 50% of the soil is piled on the lower side of the pit to trap any soil water in case of run – off.

The technology was first used in the field of agricultural production in Burkina Faso in 1973. It was promoted there by a farmer, *Yacouba Sawadogo* (Kaboré & Reij, 2004). It has since been used in Niger, Mali, Ethiopia and recently, in Kenya (Kathuli & Itabari, 2015). It is used in drought prone areas to help in the retention of soil moisture as well as in increasing manure use efficiency. Using this method, water is retained in the plant roots longer than any other method of farming, maximizing its use for plant production. When the water is retained longer, the quality of the plants is increased in terms of their health (reflected in the growth parameters) and this leads to increased yields.

Various types and sizes of *Zai* pits have been used in various parts of Kenya including, the "five by nine" pit in the Kirinyaga, Mbeere, Murang'a and Machakos Districts, and the large "Tumbukiza pits" in the Nyando District of Kenya (Danjuma & Mohamed, 2015).

In Kenya, *Zai*-pits technology has been used in Makueni, Machakos and Laikipia counties that lie in the ASALs parts of the country, where the local farmers have been urged to adopt the technology in the attempt to restore soil fertility, hence boosting the land productivity (Manzekea *et al.*, 2017) that will in turn raise the standard of living of the people in the ASAL areas. An experiment carried out in Machakos county led to a significant ($P<0.05$) increase in grain yield of sorghum from *Zai* pits with no nutrient inputs, ten times over the yield from the flat lands (Kathuli & Itabari, 2015). Despite the attempts by the *Matungulu Women Group* (Susan, 2017) to encourage and educate the farmers, there is still low adoption of this technology due to inadequate information about the technology (Kimaru – Muchai *et al.*,2017) as well as the concern by the locals that the pits are hard to dig and need a lot of labour, suggesting that they need higher capital at the initial stages of implementation.

Due to strain of the cost of initial implementation and maintenance, the pits are dug during off-season, in the event of occurrence of random rainfall (Susan, 2017). This is because during the off – season, there is relatively few "other" farm activities being carried out, and rainfall occur in unexpected days, hence there is extra time to invest in digging the pits as well as the fact that the ground will have been softened by these rains hence easing the digging of the pits. Maintenance of the pits for subsequent planting for the next growing period/season is also done during the off – seasons.

1.2 Statement of the Problem

Drought hinders crop production in most Arid and Semi – Arid parts of the world (Mathuku, 2016) and Kenya is not exceptional. This is due to low water supply, hence low water storage in these soils, reducing the amount of water that is available for plant uptake

In the present/current condition, farmers in some parts of the country, that fall under ASAL regions, cannot produce enough agricultural products to support themselves for subsistence usage. This is the case due to the fact that agriculture in these regions is always associated with low yields at the end of each growing season. The low yield is attributable to various challenges, including low soil fertility and other management problems, but the main constraint limiting production in ASAL areas is low soil water, hence low plant available water. The low plant available water is due to high evapotranspiration (Simon *et al.*, 2018) as well as low unpredictable rainfall. The low soil water is also contributed by run-off that drive away most of the rainwater after precipitation. These factors instantly reduce the amount of water available for plant uptake, resulting in insufficient soil moisture content (Liang *et al.*, 2002) to support plant growth.

Use of *Zai* pits can enhance soil moisture for plant growth support. However, technology has been used in the study of soil moisture, but some aspects still raise questions. These are the areas that my study is looking forward to address. One, there is limited information on the extent to which soil water is increased, as well as the amount of the water stored that is actually available to the plant. Secondly, little is known on the effect of *Zai* pit technology on crop water use efficiency. Third, specific depth of *Zai* pit to be used with a combination of recommended amount of manure in ASAL regions is not clear, yet this has a bearing on gross profit margins.

1.3 Objectives

The research comprised of two levels of objectives, namely broad objectives and specific objectives.

1.3.1 Broad Objective

The broad objective of the study was to contribute towards enhanced cowpea production in selected dry areas of Kenya through the application of Zai pit Technology.

1.3.2 Specific Objectives

The study had four objectives, which were as listed below:

i. To determine the effect of *Zai* pit technology on soil volumetric moisture content and water use efficiency (WUE) of cowpea (*Vigna unguiculata* L. Walp) in ASAL localities Katumani (Machakos County) and Naivasha (Nakuru County)

ii. To determine the combined effect of *Zai* pit technology and manure on selected soil properties, growth and yield of cowpea.

iii. To assess gross profit margin of using *Zai* pit technology in comparison to use of flat land in cowpea production

1.4 Hypotheses

These had been derived from specific objectives, and were as listed below:

i. Combining *Zai* pit technology and manure has no significant effect on soil properties, growth and yield of cowpea.

ii. Using *Zai* pit technology has no significant effect on soil volumetric moisture content and water use efficiency (WUE) of cowpea (*Vigna unguiculata* L. Walp).

iii. There is no significant difference in gross margin between using *Zai* pit technology and Flat plots in Cowpea production.

1.5 Justification

As mentioned, 80% of Kenyan land experience arid and semi-arid characteristics. This percentage is likely to increase due to effects of global warming that lead to change in precipitation patterns, hence diminishing farm produce. With the adoption of *Zai* pit technology as a planting technique, the problem of low agricultural production due to drought problems would be minimized as the technology helps in the conservation of soil water, hence increasing the soil moisture storage. The pits also help in increasing nutrient use efficiency and reduction of water loss as well as manure/nutrient loss. *Zai* pits can lead to increased plant available water since they collect runoff and concentrate it just at the root zone. This technology enhances soil water content (Santra *et al.*, 2018) at the root zone as well as prolonging the time that the water stays available to the plants, hence the plants are in a better position to utilize the water maximally to achieve higher yields.

The rain water that would otherwise be lost through run-off are collected in the pits. The collected water, plus manure that is mixed with top soil, helps in soil moisture conservation. Once the water is conserved it increases the soil moisture content at the root zone for plant uptake, leading to increased water use efficiency. The increased soil moisture content enhances plant growth and development that finally lead to an increase in production.

These ASAL regions don't support production of all crops. Cowpea is a leguminous crop that is in a position to tolerate low soil fertility and erratic rainfall. It fixes its own nitrogen hence improves the nutrition status of the soil. It also utilizes little available water and have very short production period. These characteristics makes it best choice for production in arid areas and farmers can obtain better yields.

The high farm yield will in turn help in raising the living standard of the ASAL farmers and the general communities, since they will get higher returns from the sale of their produce. This work will also benefit extension officers as they strive in advising the farmers of the better technologies of increasing production from their farms.

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CHAPTER TWO

LITERATURE REVIEW

This chapter gives an overview of the brief history of Zai pit technology and its spread within Africa and its applicability. The chapter explains the relationship of Zai pit technology to volumetric moisture content, chemical properties, cowpeas growth and development, water use efficiency and finally, its effect on gross margin.

2.1 Brief history of *Zai* pit Technology

Zai is a term used by the local Burkina Faso farmers in reference to small pits for planting, which are relatively larger than the normal planting holes and have various sizes, depending on the type of plant to be grown and the slope of the farm as well as the amount of rainfall received in the region (Danjuma & Mohammed, 2015).

It (*Zai* pits) is a water harvesting technology that has been used for over a century in Burkina Faso (Partey *et al.*, 2017). It is designed to collect the rainwater runoff and concentrate it in the root zone, so that it can be utilized by the plants (Kabore & Reij, 2004). Up to the late 18th century, its full potential had not been utilized until a farmer, *Yacouba Sawadogo* decided to improve it by adding some manure to the pits. The outcome was very significant as compared to the previous years when neither *Zai* pits nor manure were used in crop production (Sawadogo *et al.*, 2001).

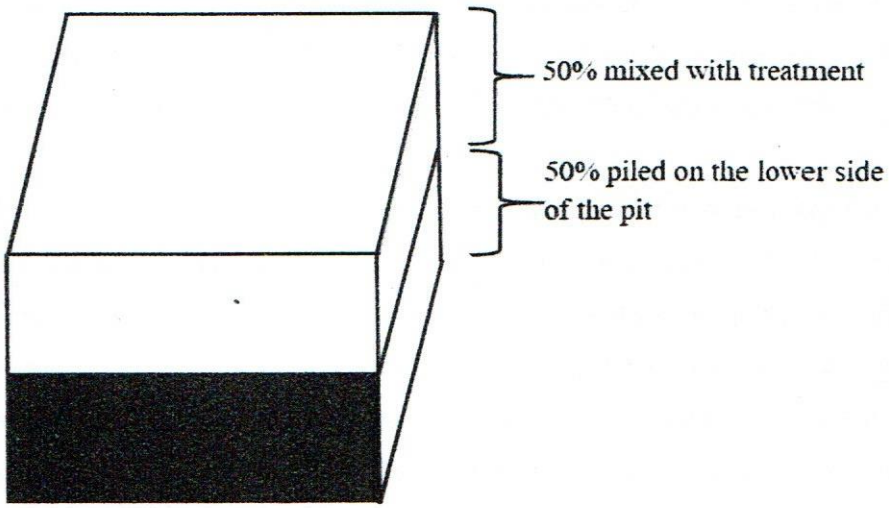


Figure 2.1: *An example of Zai pit establishment*

In the attempt to advance it, Sawadogo (2011) used the *Zai* pits Technology to reclaim the Arid and Semi-Arid lands of the Northern Burkina Faso. This bore enough fruits to open the eyes of the ASAL communities of the country who had totally given up in agricultural

productivity of their farms and resorted to other options like pastoralism, while others migrated to the urban centres for alternative jobs in towns (Kabore & Reij, 2004; Wouterse, 2017).

The efficiency and high returns from the fields where the technology ensured its spread throughout Burkina Faso and across the boarders to the neighbouring countries like Mali and Niger. In Niger, the farmers that applied the technology benefited since they had high returns from their farms. They even gave it a local name, *Tassa* (Motis *et al.*, 2013). From Niger, it spread to various North African countries and farmers appreciated its benefits (Danjuma & Mohamed, 2015). It later spread to east African countries, with Ethiopia being the first to test it in the Northern Ethiopian highlands (Amede *et al.*, 2010) where it was tested with potato and beans. The results from these were quite significant.

Zai pit technology was later used in Kenya for the first time in 2005. It has been used in the coastal region in maize production (Saha *et al.*, 2007). Up to date, it has been used in Kilifi county, Makueni county (Muriu *et al.*, 2017), Trans Nzoia county, Tharaka Nithi county (Serah, 2017) and Machakos County. It is referred to in different local languages in the country, including "Tumbukiza" (KARI 2014), and "five – by – nine" (Serah, 2017).

2.2 Applicability of *Zai* pit Technology

This technology focuses on harvesting water that is lost rapidly through runoff and conserving it for a longer time in the soil, at the same time concentrating it to the root zone for plant uptake and utilization in the plants. According to research done by Sawadogo *et al.* (2001), *Zai* pit technology utilizes both gravitational and capillary water that would otherwise be lost. This water is concentrated at the root zone hence the plants are in a position to utilize it.

Zai pit is a technology that has existed over centuries, but it is recently that it was improved by Sawadogo *et al.* (2002) through addition of manure to improve fertility and boost their production. Manure serves numerous purposes, among them, improves soil physical characteristics through particle aggregation (de Oro *et al.*, 2019), improves soil porosity through particle aggregation as well as through movement of the termite that reside in the manure as they burrow through the soils, boosts the fertility of the soil (Lee & Foster, 1991) through availing plant available phosphorus, potassium and nitrogen in form of nitrates from the nitrification process (from ammonia) (Paul, 2014)

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$$

In addition to the above advantages, when FYM is used in combination with *Zai* pit, which is a water harvesting technology, high yields are guaranteed and this can even lead to a

100 % profit (Serah, 2017). *Zai* pit technology also utilizes different sizes of the pits depending on the area and climatic conditions of the region (Kathuli & Itabari, 2015).

Different *Zai* pit sizes need different amounts of FYM for crop production, for instance the "five by nine" pits, which have 500 cm x 900 cm in dimensions as the name suggests, that has been used by KARI (2014) in Trans Nzoia County, in Kenya for growing grass. Matungulu women group (Susan, 2017) indicate that larger *Zai* pits (100 cm by 100 cm) should utilize a 20-litre full bucket of FYM while smaller ones (70 cm by 60 cm) is to be supplied by half of the 20 litre bucket of FYM. This manure is mixed thoroughly with the top soil that was set aside during digging of the pits. The mixture is then returned back into the soil. This helps in improving the various soil properties.

Mixture of soil and FYM helps in soil aggregation, hence improving water retention. Once this retained water is availed to the plants, soil fertility chips in as a factor to limit growth and final productivity of the soils. The ASAL soils are eroded and have low fertility (Mulinge 2016). Therefore, boosting soil fertility must be factored in for favourable outcomes in terms of plant health (by reducing nutrient deficiencies) and yield. To take care of fertility problems, manure has been used in combination with *Zai* pits in the attempt to increase the yield, and this has been proved by Fatondji *et al.* (2011) to increase yield by 60%. The manure in the pits also have another function, of attracting termites. These termites help in improvement of aeration in the soils in the *Zai* pits (Fatondji *et al.*, 2007). Improving the aeration of the soil by the termite as they move through the soil has also been observed (Zelelew & Melesse, 2018) but the degree to which porosity is affected has never been quantified.

Zai pit technology can also be used in soils that have been crusted and contain hard pans that hinder growth and development of the plant roots. When the growth of roots is hindered, plants suffer water stress and this leads to wilting and final death of the plants. *Zai* pits can reclaim these lands since it reduces water runoffs by concentrating the water in the pits, this reduces crusting (Schuler *et al.*, 2016), while helps in the breaking of the hard pans since after digging the pits, the lower 50% from the pit is discarded, while the top 50% is mixed with manure before being returned back to the pit. Overall, these lead to reduction of bulk density, allowing root penetration, thereby favouring root growth.

In the recent past, *Zai* pits have been used in combination with inorganic fertilizers in the attempt to better the final produce from the farm. Inorganic fertilizers are fast releasers of the required nutrients and in the right amount for the plants. This makes them a better choice to aid in case of observation of a deficiency in the plants. Inorganic fertilizers also aid in precision farming, i.e., after soil test, an exact amount of the deficient nutrient can be quantified

hence exact amount of the inorganic fertilizer is applied to ameliorate the soil and return it back to its productive state. For instance, according to a research conducted by the Kenyan government under the program NAAIAP (Sheehan *et al.*, 2014), it was shown to boost the soils of the Gem Sub-County, Siaya county, Kenya, a farmer is supposed to add 250 Kg/Ha of N: P: K processed with ratios of 17:17:17 and a top dressing with CAN at the rate of 125 Kg/Ha. With this precision in nutrient application combined with manure to improve the soil structure and *Zai* pits to help in boosting soil moisture content, plants can experience a favourable soil environment that can lead to higher yield. Such a technology can help in increasing the productivity of the ASAL soils and hence make the lands agriculturally viable. At the same time, the technology can lead to reclamation of these degraded unproductive lands, thereby reclaiming them.

2.2.1 *Zai* pit effects on Soil Volumetric Water

Zai pit technology is a technology that is capable of improving the physical properties of soil and make it favourable for crop production. This has been proven in areas that have faced serious soil degradation (Fatondji *et al.*, 2011). *Zai* pits technology impact highly on the soil structure, bulk density, soil porosity, water infiltration and soil water content. All these physical properties have great influence on the plants' growth and development (Hillel, 2003), hence affects the final crop yields from a farm.

Zai pit technology, with the help of the added manure, improves soil structure by binding the soil particles together into aggregates (Rabot *et al.*, 2018), which are better aerated, have high water retention capability and have low bulk density (Yegon *et al.*, 2016). These qualities help in improving the soil for crop production and better final yield.

Volumetric moisture content is also influenced by the bulk density. Soil bulk density is an expression of the weight of the dry soil solids to its given total volume (Hillel, 2003). It is used to estimate the degree of compaction of the soil. The compactness of the soil determines its agricultural productivity since it determines the amount of water that flows through the soil, and once it exceeds the favourable range for crops, the final produce in terms of yield is greatly reduced (SQPTL, 2019). When soil is highly compacted, the elongation of the plant roots is minimized since root penetration is impaired and water circulation in the soil is affected negatively. This means that the crop is cut short of its quench to reach for the soil water (Beach & Flood 2016) for uptake as well as the nutrients that it needs for its survival. To reduce the bulk density of the soil, its compactness must be reduced.

Arid and semi-arid lands are mostly characterized with sandy soils. The sandy soils are poor in crop production, and one of the main reasons contributing to its least agricultural productivity is that it is characterized by high bulk density, this is attributed to the fact that it has larger amount of gravel and sand particles. Another reason for poor performance of the sandy soil is the fact that they have low water retention capability, hence minimal water available for plant growth. For better yields, the high bulk density must be reduced. Reduction of the bulk density can be achieved through the application of the *Zai* pit technology (Vanlauwe *et al.,* 2002). According to the research carried out by Kimaru – Muchai *et al.* (2017), the latter is because during the digging of the pits, the top soil that is returned back into the pit is mixed with the farmyard manure that help in the aggregation of the soil particles together, hence improving the soil porosity and thereby lowering the bulk density of the soil. This boosts the final yield from these soils treated by this technology.

Volumetric water content of soil is also affected by soil pore size and their distribution in relation to the soil's particle size distribution (Chen *et al.*, 2015; Lal & Shukla, 2005). Crop production greatly depend on these pore spaces in that the form entry points as well as channels for flow of water and air. This is the water that contributes to the volumetric water content up-taken by the plant. This water helps in the dilution of plant nutrients hence helps in availing them to the plants, improving its health. The water also helps in cooling of the plants, i.e., through transpiration. The soil pore spaces also avail the air to the soil and plant roots. Soil macro- and microorganism utilize this air for respiration hence their survival deep in the soil horizon, whether in the rhizosphere or in Non-rhizosphere (Mando & Miedema, 1997).

The technology being proposed has the ability to improve the soil water circulation in the ASAL soils characterised by hard pans, which hinder water penetration and air circulation into the root zone, hence this is a reason to encourage its adoptability (Sawadogo, 2011). Here, it is important to note that the *Zai* pits helps in facilitating water infiltration into the rhizosphere, hence minimizing the (little) rain water that would have been lost through run-offs. This helps in harvesting the water and concentrating it at the root zone hence better utilization by the crops to better the final yield (Serah, 2017).

The volumetric water content is an important parameter in the study of the soil moisture in relation to crop production. It is the per-volume soil water content that is measured as the ratio between the volumes of water contained in a soil sample to the total soil sample volume. Volumetric water content is important in crop production since too little of it can lead to plant death, hence reduce the yield, while too much can lead to root disease and a wastage of water. Water is a delivery system that transports the plant nutrients, making them readily available for

plants' uptake. It should be managed and utilized properly, as the plants' entire survival depends on it since it leads to better nutrient management (Kimaru - Muchai *et al.*, 2017).

Zai pit technology ensures timely delivery and maintenance of the water at the root zone. This ensures water and nutrient availability to the plants, hence proper utilization. The water that is availed to the plants for uptake is from the rain water run-off. This is achieved through strategies that are put in place during the designing of the pits, ensuring that rain water is trapped in the pits hence concentrating it around the root zone. Since agro-ecological zone IV is characterized by low rainfall (Mathuku, 2016), the *Zai* pits aims at capturing most of the gravitational water before it is drained off, to maximize its usage by plants.

2.2.2 *Zai* pits and Soil Chemical Properties

As the technology aims at improving the physical properties of the soil, the chemical properties are also improved along the process. These chemical aspects help in better delivery of the plants nutrients in the available forms and in the right quantities for crop production (Okalebo *et al.*, 2002). Some of the chemical properties that are affected positively include soil pH, exchangeable acidity, extractable phosphorus, inorganic nitrogen.

Zai pit technology plays a role in soil pH optimization in that the use of farmyard manure that is added helps in lowering the acidity (raising pH) of the soil (Warmer, 2019) due to the presence of magnesium and calcium. The magnitude of the change in pH depends on the amount of the FYM added per plating pit (Ano & Agwu, 2004). Therefore, the *Zai* pit technology can help in the amelioration of the soil acidity around the root zone, thereby increasing the solubility of phosphorus, hence making it available by transporting it to the root zone where it can be accessed by the plants (Duruigbo *et al.*, 2007).

Zai pit technology helps in the correction of the exchangeable acidity. This is achieved by the organic manure that is added to the pits through ion exchange reactions which occur when terminal OH^- of Al or Fe^{2+} hydroxyl oxides are replaced by organic anions which are decomposition products of the manure such as malate, citrate and tartrate (Pocknee & Summer, 1997).

Zai pit technology also helps in increasing soil fertility, which is achieved through addition of more plant nutrient elements including nitrogen, phosphorus and potassium. These elements come from the breakdown of the added manure into their inorganic forms that can be utilized by the plants (Duruigbo *et al.*, 2007), while some of them are present in the soil naturally, as well as from the fertilizer added from the previous growing seasons. This in turn boosts the extractible phosphorus and inorganic nitrogen. And all of them are availed to the

plants through the water that is harvested by the *Zai* pits, hence delivering them to the root zone for uptake and utilization by the plants.

2.2.3 *Zai* pits and Plant Growth Parameters

While trying to boost the soils' general properties, (including physical, chemical and biological properties), all these are geared towards improving crop productivity. Productivity is reflected in different characteristics and can be measured from the growth parameters and the final yield of the crops cultivated (Obi & Ekperigin, 2001). The crop productivity is greatly reduced by the climatic conditions which vary from one geographical location to the other, like, ASAL regions are always characterized by poor quality yields, which are reflected early enough in their growth and development stages by the various growth parameters (Mutungwe *et al.*, 2016).

The various growth parameters that are influenced by the *Zai* pit technology may include days to emergence which is influenced by the moisture conditions of the soil around the seed, which influence crop germination (Olatunji *et al.*, 2016). When the moisture in the soil is favourable and the soil is not compacted, the plants will emerge after few days of planting. *Zai* pit technology ensures favourable moisture conditions through harvesting of the rain water and collecting them around the root zone. As the dug top soil is returned back into the pit after mixing it with the FYM manure, the bulk density is reduced as well as its compactness.

Plant height is a parameter that is also affected in the crops that are cultivated in the arid and semi-arid lands (Rusinamhodzi *et al.*, 2017). For favourable/required plant height to be achieved, the soil moisture must be at a desired level. This is because moisture level, as they interact with the nutrient availability in the soil are contributory factors to the plant biomass and the final yields of cowpeas (He *et al.*, 2019; Onyeneke & Madukwe, 2010). Higher moisture level, as availed by the harvested water from the *Zai* pits into the root zone, as well as the soil nutrients as availed to the plant roots by the water collected and the added manure facilitates the plants' growth hence favourable plant height is achieved. This height will in turn be in a position to sustain higher number of pods that will finally maximize the yield from the farm.

Once the plant height is favourable, other parameters will also be influenced, for instance number of branches per plant as well as number of pods per plant (Saha & Muli, 2018). The later will have a great influence on the final yield from the farm.

Stem diameter is also a parameter that is strongly dependent on the soil moisture characteristics. When the plant is exposed to severe water stress and with a combination of low soil fertility, as in the case of the ASAL regions, the stem diameter is reduced and it may not be in a position to support numerous pods, hence leading to low yields (Kathuli & Itabari, 2015). *Zai* pit technology harvests run-offs and collects it in the root zone (Amede *et al.*, 2010). When this water is available, plant nutrients are also available from the bulk soil as well as from the added manure/fertilizer. In turn, the stem diameter is increased that can support the plants in case of adverse weather conditions, hence better yield is achieved at the end of the season.

All the above listed parameters when kept at favourable levels, including soil's physical and chemical conditions, the final yield is maximized. This is the main reason as to why the *Zai* pit technology has been improved chronologically, from the advancement by Sawadogo *et al.* (2002) to the modern pits. The technology aims at reclaiming the arid and semi-arid lands, which goes hand in hand with boosting the crop production from these soils that is reflected in the better yields.

2.2.4 *Zai* pits and Water Use Efficiency (WUE)

In ASAL regions, nutrients and crop management constitute some of the key factors affecting crop production. The soils in these regions are characterized by low fertility and inadequate unpredictable rainfall that greatly affect the soil moisture level. *Zai* pit technology looks forward to address all these problems and aims at increasing productivity of these soils. Water use efficiency (WUE) is one of the ways of gauging the level of productivity of soils, through the plants that grow in them (Limousin, 2018).

WUE is the measure of the plants' ability to convert water into biomass. It relies on the soil's capacity to capture and store water as well as the crops ability to access the water stored in the soil and use it for its (crops) development (Saha *et al.*, 2009). Water use efficiency has been shown to increase with decrease in evapotranspiration. Sharma *et al.* (2015) indicated that water use efficiency also increases with increase in crop water supply up to a certain point. This is the reason why increasing the water content at the root zone through harvesting it will have an impact on water use efficiency (Leakey *et al.*, 2019). Sharma *et al.* (2015) also showed that increasing water supply also increases fertilizer use efficiency, through increasing the availability of the applied nutrients to the planted crops. These, thereafter, have an impact on the final yields, and yield components.

WUE can be used to compare the amount of water taken up by the plants in *Zai* pits and those planted in flat land. According to FAO (2017), the WUE is between 60-65% in Burkina Faso and 62-77% in Morocco.

Water use efficiency can be computed in two ways, which both reflects the plants' ability to utilize the water that was availed during its growth and development. It can be computed by getting the ratio of the plant biomass produced to the rate of transpiration (Tfwala *et al.*, 2018; Unkovich *et al.*, 2018) during the growing period. This is called Biological water use efficiency.

Biological Water Use Efficiency (**WUE-b**) = $\frac{\text{Total dry matter}}{\text{ETR}}$ (Kg/ha/mm).....*equation 2.1*

Where, ETR = evapotranspiration

It can also be computed from the final yields, i.e., the grains harvested from the farm. This is called Grain water use efficiency and it also utilizes the transpiration rate (Karthika *et al.*, 2019) during its calculation, as below;

Grain Water Use Efficiency (**WUE-g**) = $\frac{\text{Grain yield}}{\text{ETR}}$ (Kg/ha/mm) .....*equation 2.2*

Where, ETR = evapotranspiration.

2.3 Cowpea growth requirements

Since the dryland areas have limited soil moisture, they only support certain species of crops. These are crops that are adapted to the low soil moisture conditions and are able to survive under water stress, but to a certain level. If the conditions become severe, they can lead to total loss i.e., up to 100% loss. One of the plants that are drought tolerant is cowpeas (*Vigna unguiculata*). It does well in the semi-arid tropical regions associated with nutrient depleted soils, covering Asia, Africa, southern Europe, and Central and South America (Stancheva *et al.*, 2017).

Cowpea is one of the leguminous crops that is tolerant to adverse weather conditions, including soil moisture stress (Rusinamhodzi *et al.*, 2017) and has the ability to withstand drought and short growing periods (Ouda *et al.*, 2021). It can do well in soils with more than 85% sand, less than 0.2% organic matter content and is associated with low phosphorus (due to its low mobility) (Singh *et al.*, 2003). Cowpeas also has the ability to fix the atmospheric nitrogen through the root nodules, hence an advantage as it avails the nutrient for its own use, giving it a higher chance for survival in the arid areas that are associated with low fertility conditions. According to the study carried out by Stancheva *et al.* (2017), nitrogen fixation needs water availability in the soil. Therefore, utilizing the water harvesting technology for

cowpeas production will boost rhizobium activity in the root nodules (Onyeneke & Madukwe, 2010), that will significantly increase the rate of atmospheric nitrogen fixation.

It requires well-drained soils which are less restrictive to the root penetration. It is tolerant to infertile soils and prefer a soil pH of 5.6 - 7.5. Its production is affected with cold conditions, hence does well in warm conditions with atmospheric temperature of 20 – 30 °C, with an annual rainfall of 300 – 600 mm and prefers an altitude of 0 – 1600 m above the sea level (Boukar *et al.*, 2019). In Kenya, it is mainly produced in Baringo, Trans Nzoia, Kitui, Migori, Kisii, Kakamega, Machakos, Makueni, Tharaka Nithi, Kwale and Kilifi counties, where different varieties are grown depending on the agro-ecological conditions of the area (Morris *et al.*, 2016; Saha & Muli, 2018).

Kenya is divided into seven (7) Agro-ecological zones (AEZs) with different climatic characteristics (FAO 1996). The different climatic conditions affect plants to be grown in these areas as well as the varieties to be used (Agbogidi & Egho, 2012; Ouda *et al.*, 2021). This leads to the existence of different cowpeas varieties that are adapted to the different AEZs (Okeyo-Ikawa *et al.*, 2016). Machakos 66 (M66) is a spreading variety that that was developed for arid areas and can be grown for both leaves and grains. It takes 80 – 90 days to mature and has a grain yielding range of between 750 Kg/ha to 1750 Kg/ha. The M66 variety has proved tolerance to virus and scab as well as aphids. The Katumani 80 (K80) is also a spreading variety and has purple flowers. It has a maximum yielding of 800 Kg/ha and is tolerant to foliar fungal diseases and leaf mosaic virus. KVU 27-1 is also a multipurpose variety, for its ability to do well when grown either for leaf or grain. KVU 27-1 has a maximum yielding of 1,500 Kg/ha and is moderately tolerant to aphids, pod borers and leaf hoppers and is resistant to foliar fungal disease and mosaic virus (Saha & Muli, 2018). Other varieties include Kunde 1, MTW 63, MTW 610 and Kitui Black Eye (GLCPA, 2018).

With the application of *Zai* pit technology, better results are expected, for instance, it is predicted that the grain yield will be higher than the above expectations. The prediction is based on the expected soil physico – chemical parameter improvements by the *Zai* pit technology.

2.4 Gross Margin in agricultural production

Gross margin is an accounting derivative that gives the financial performance of an individual agricultural enterprise/venture (Devkota & Yigezu, 2020). It helps in determining the performance of an enterprise, venture or project as per a given period of time (period of operation), which can be a planting season or a financial year (Zarzecka *et al.*, 2020). It can

also be used to compare different sections or departments in the same project or agricultural farm.

GM is very important since it helps in making important management decisions in a project, for instance, how to regulate various inputs with the main aim of expanding the output. Can also help in determining best markets for the produced commodities in order to maximize profits (Elouadi *et al.*, 2020). GM calculated by getting the difference between gross income and the total variable cost of a project or enterprise.

While doing the calculations, it is important to note the currency that you will be using, and this should be constant throughout the process. In agricultural crop production, GM calculation should incorporate inputs like the cost of tangible materials (land preparation, planting seeds, irrigation, fertilizers and pest control, harvesting, processing and packaging, storage, fuel cost and rent among others (Devkota & Yigezu, 2020)), labour cost and cost of machinery where applicable. In cases of animal production, cost of feeds, drugs for treatment and vaccination must be included (Kontsevaya *et al.*, 2020). The sum of all these gives the "Total variable cost", which is subtracted from the total revenue to obtain the gross margin (Zarzecka *et al.*, 2020). From these, proper book keeping should be done from the onset of a project to the end of the required period, to provide the accurate figure of the amount of money that has been spent in the running of the project.

Larger gross margin implies that the project or enterprise is making good profit and is able to sustain itself for a longer period of time. Application of *Zai* pit technology helps in enhancing yields, which will fetch high income. This, will later lead to greater gross margin, thereby making farmers achieve their goal of getting the most from their farming ventures.

2.5 Summary of Research Gap based on Literature

Zai pit technology, therefore, is a versatile technology that can be used in solving different soil problems simultaneously i.e., soil moisture conservation, rainwater harvesting, concentration of nutrients at the root zone, improving soil structure and enhancing soil microbial activity.

Based on the literature reviewed, little is known about the impact of *Zai* pit technology on water use efficiency, which is a function of yield, hence quantification of the effect is key. Determination of the depth of *Zai* pit to be used by a recommended rate of manure in the two identified location should be documented, since each location experience different rainfall amount every year all over the country. This calls for appropriate size of *Zai* pit to prevent concentration of either too much water to lead to flooding or too low water to starve the crops.

CHAPTER THREE

ZAI PIT EFFECTS ON SELECTED SOIL PROPERTIES AND COWPEA (*Vigna unguiculata*) GROWTH AND GRAIN YIELD IN TWO SELECTED DRYLAND REGIONS OF KENYA

Abstract

Erratic rainfall and temperature regimes, strongly affects agricultural productivity. To address the reduction in production, this study assessed the effect of *Zai* pit technology on selected soil properties and cowpea growth and grain yield. *Zai* pit technology was tested in two locations falling under Agroecological Zone IV (relatively dry areas) i.e. Katumani in Machakos County and Naivasha in Nakuru County, Kenya, aiming to determine the combined effect of four *Zai* pit depths and two levels of manure (plots with manure and plots without manure) on selected soil properties, growth and yield of cowpea. Experiment was laid out in split plot arrangement, with manure levels as the main plot factor and *Zai* pit depths (Flat -Z_0, 30 cm – Z_{30}, 45 cm – Z_{45} and 60 cm – Z_{60}) as subplot factor, replicated four times. Cowpea (M66 variety) was used as the test crop. Inorganic nitrogen (N_{in}) and extractable phosphorus (P_{ex}) were significantly ($P < 0.05$) higher, at 1.37 $mgkg^{-1}$ for N_{in} and 80.4 $mgkg^{-1}$ for P_{ex} in *Zai* pits compared to flat plots which were at 0.91 $mgkg^{-1}$ for N_{in} and 47.1 $mgkg^{-1}$ for P_{ex}. The values of N_{in} and P_{ex} also varied depending on depths, with Z_{45} having highest N_{in} at 1.17 against the least, at 0.89 in the Z_0, while Pex was highest in Z_{30} at 102.3 $mgKg^{-1}$ while Z_0 having the least P_{ex} of 89.7 $mgkg^{-1}$. Generally, crops in *Zai* pitted plots were larger in diameter (0.46 cm) and height (34.20 cm) than crops in flat plots at (0.42 cm) and (18.11 cm) diameter and height respectively. Better performance was observed in yield, with Z_{45} yielding 853.33 $kg.Ha^{-1}$ against 685.0 $kg.Ha^{-1}$ in Flat plots in Katumani while 931.66 $kg.Ha^{-1}$ in Z_{45} against 563.33 $kg.Ha^{-1}$ from Flat plots in Naivasha. This study demonstrated great potential of *Zai* pit technology on crop production, as reflected on improved growth and yield of cowpeas. Combining *Zai* pits with manure increases soil N_{in}, P_{ex} and is a guarantee of great crop performance in terms of high final yields.

Keywords: *Zai* pits, ASALs, Soil moisture, Dryland Agriculture, Cattle manure, Inorganic Nitrogen, Extractable Phosphorus.

3.1 Introduction

Aridisols are degraded soils, mostly found in relatively dry areas experiencing unreliable rainfall regimes. The low quality of soil and low rainfall minimizes agricultural activities that can be carried out in drylands (Naba *et al.*, 2020). For farmers determined to

cultivate these soils, they end up producing little that can only support their subsistence till next production season, making it difficult for commercialization. With the current global warming, climate change is inevitable and aridisols continue deteriorating, hence farmers producing less than previously (Mwangi *et al.*, 2020). Reduction in rainfall intensity and duration results in low soil water storage, which reduces soil moisture availability that greatly affect crop production. Water is a critical factor of crop production and before planting, farmers have to consider its source. Some farmers are able to irrigate, while those who cannot afford rely on rainfed crop production, which proven to reduce production expectations seasonally. Alternatively, soil moisture conservation measures can be adopted, which include the use of *Zai* pit technology (Kimaru – Muchai *et al.*, 2020).

Zai pit technology uses holes dug in the soil for planting crops to help in soil moisture retention and nutrient/fertilizer maintenance. It is a water harvesting technology (Partey *et al.*, 2018) that is suitable for areas with unpredictable rainfall and low soil fertility, hence subsequent crop failure. The rain water that would otherwise be lost through runoff are collected in the pits, hence stay longer and are utilized slowly by the plants for various physical, biological and chemical processes (Serah, 2017). This helps in the reclamation of the drought stricken Arid and Semi-Arid Lands (ASAL) back to their originally productive status (Kimaru – Muchai *et al.*, 2020). *Zai* pit technology also helps in reducing waste of fertilizer and manure, and increase their efficiency (Naba *et al.*, 2020) since instead of being applied in the whole field, the manure is only applied in the pits in which the crops are to be grown. The manure, or any soil treatment, is mixed with the upper 50% of the soil, which is then returned back to the soil, while the lower 50% of the soil is piled on the lower side of the pit to trap water in case of any run – off.

The technology, in combination with organic manure, especially Farmyard Manure (FYM) have great influence on selected soil properties (Pocknee & Summer, 1997), which in turn significantly influence growth and development of crops as well as the final yields. Among soil properties influenced are soil inorganic nitrogen and extractable phosphorus. P and N are two out of the three major nutrients needed in abundance by the plants throughout, for completion of their growth cycles.

Nitrogen makes up almost 80% of the earth's atmosphere. It is also found in the bodies of all living organisms including plants, taking part in their growth and development. Amount of Inorganic nitrogen (N_{in}) in the soil depends on the N – pools in the soil (Omara *et al.*, 2020), as well as the amount of added organic/inorganic fertilizers, which add N in different forms. Organic fertilizers like farmyard manure undergo decomposition to release nutrients, majorly

N and P that are utilized by plants (Yang *et al.*, 2020). Decomposition is the process by which the microorganisms in the soil attack dead biomass, primarily in search or energy and in the process, nutrients are released to the soil. If the applied manure contains higher amounts of Nitrogen than in the surrounding (i.e., C:N ratio of less than 25:1) (Paul, 2014), N mineralization takes place, availing it to plants in form of inorganic Nitrogen.

The various inorganic forms of N soil include ammonium (NH_4^+), nitrite (NO_2^-) and Nitrate (NO_3^-) (Clunes *et al.*, 2020). NH_4^+ is the most reduced form and found in anaerobic surroundings while NO_3^- is the most oxidised form of N_{in} and exists in most aerobic environments. They are also very soluble and availing water in the *Zai* pits makes them readily up – taken by plants.

Phosphorus is the next important plant macronutrient element in the soil and it is very important yet very limiting in plant growth and development (Das and Das, 2020), since it might be present in soil in abundance but not available for plant uptake. This is contributed by its immobility in soils, hence to make it mobile, pH must be adjusted to favourable ranges of between 6.2 – 6.8 (Hu *et al.*, 2020). Therefore, to determine the fraction that is available for growth and development, the extractable phosphorus is always fraction measured in the laboratory (Estefan *et al.*, 2013). It is available to plants in the form of primary orthophosphate ($H\square PO\square^-$) and Secondary orthophosphate (HPO_4^{2-}) (Weihrauch *et al.*, 2020).

In plant tissues, Total Phosphorus (P_T) ranges from 0.09% to 0.6% (Carver *et al.*, 2020). There are limited P toxicities, while P below this level lead to deficiencies. Phosphorus deficient produces low yields, and leads to loses to farmers, hence these should be avoided. Deficiency is first observed in the lower old leaves, which display purple or reddish brown along the edges.

Nitrogen is very vital in crop growth, and a healthy plant contains 3% – 4% of N in their above ground tissues (Akhtar *et al.*, 2020). This percentage is greater than any other elements' fractions in the tissues hence its significance. In the tissues, it is measured in form of Total Nitrogen (N_T) and it is crucial since it is the main component of chlorophyl (Arsic *et al.*, 2020). Its presence is also needed since it's a major component of amino acids, which is a building block of proteins. Proteins maintains plants upright since they form structural unts in plants cells, hence a contributes to the plants' growth in breath (stem) and height. Nitrogen and Phosphorus are also a component of adenosine triphosphate (ATP) (Zhang *et al.*, 2020), a component that assist in energy transfer, hence allowing energy conservation and use in plant cells. Both Phosphorus and Nitrogen are part of the DNA (Paul, 2014), the genetic make – up

that permit growth and reproduction. Therefore, N and P contributes to the general growth and development of plants and the final yields.

To determine the amount of agronomic P and N to add to the soil of optimum growth and good yield, soil testing is key (Hu *et al.*, 2020). Such nutrients maybe abundant in soil, but inaccessible by plants, since not in their ionic form for uptake by plants. To facilitate nutrient dissolution, water needs to be availed. *Zai* pits delivers this water through collection from rain water. Nutrients then dissolve to ionic forms, facilitating availability to plants.

Effects on the soil properties finally lead to reciprocating effect on the growth parameters of the crops and to the final yields from the farm. In this experiment, Cowpea (*Vigna unguiculata* L. Walp) was used as the test crop, and there were significant observations made. Cowpea is an excellent alternative food in the world with its origin in Africa. It is a nutritive source of Vitamin B (89.0%), Iron (53.6%), Copper (51.2%) and Phosphorus (39.2%) (Mndzebele *et al.*, 2020). *Zai* pit technology has the capability to influence growth parameters like stem diameter, height and final yield of crops.

All parameters are affected proportionately depending on the size of the *Zai* pits being used. The pits in this experiment had varying depths and were being compared to those plots which the technology was not applied to, with the aim of determining the combined effect of *Zai* pit technology and manure levels on selected soil properties, growth and yield of Cowpeas. Effect of the two different sites (but falling under the same Agro – ecological zone) were also investigated. This experiment was carried out in two sites, Katumani and Naivasha.

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3.2 Materials and Methods

3.2.1 Site Description

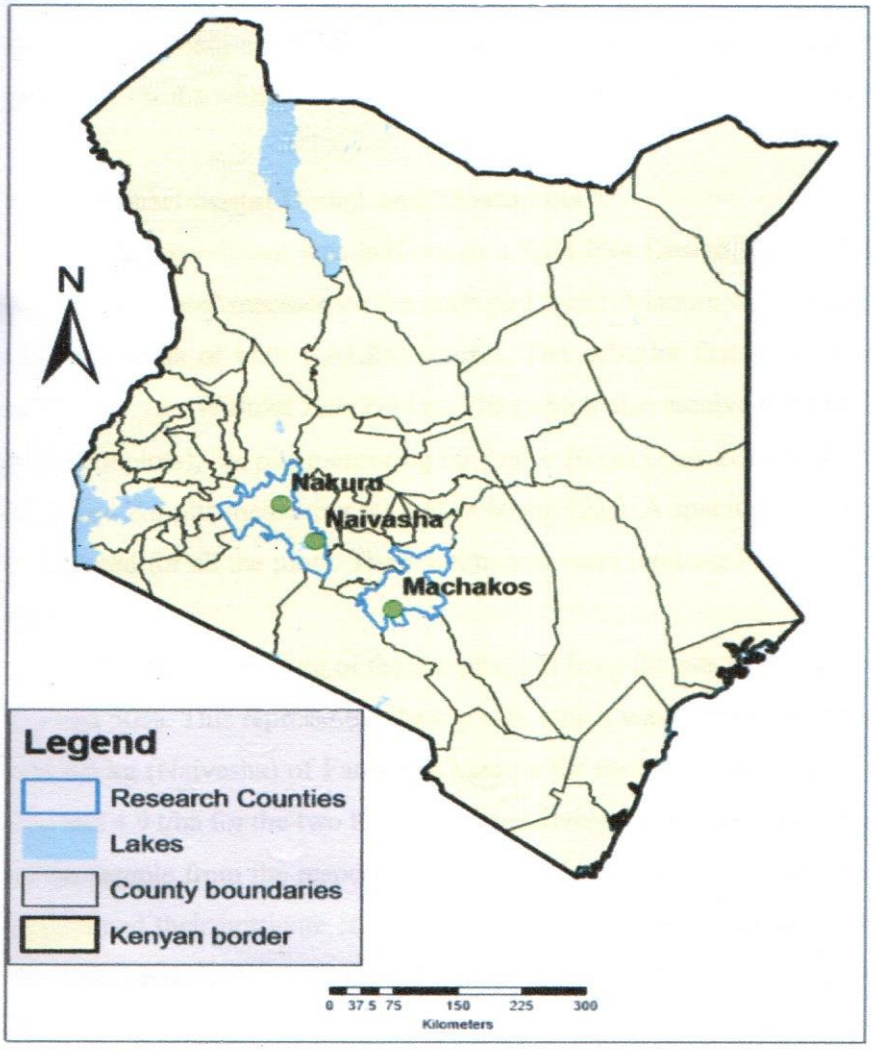


Figure 3.1: *Study sites in selected dryland regions of Kenya*

The study was carried out in two locations, which were Katumani in Machakos county and Naivasha in Nakuru county, Kenya (*Figure 3.1*). These two locations have different soil types, with different properties, main one based on the difference in their water holding capacity. This makes them differ in terms of the amount of water that they can avail to the plants due to their infiltration rates. Katumani in Machakos falls under ASAL parts of the Eastern regions of Kenya (Lilian & Mutiso, 2019). It lies in the altitude of 1200 m above the sea level (Mathuku, 2016) and is located along the longitude 37°14'00" E and latitude 1°35'00" S (GPS). Naivasha in Nakuru County experiences low average rainfall of 677 mm annually, with a temperatures range of between 9° C to 28° C. It is found in the altitudes of 2086 m above the sea level. Naivasha lies along the longitudes 36° 26' 9" E and latitudes 0° 43' 0" S (GPS).

Both sites fall under similar Agro-ecological zones IV (AEZ) (Maingi *et al.*, 2008) characterized by a lower biennial rainfall regime, with the long rains in the months of March to May while the short rains occur in the months of early October to December. The main soil types in Katumani are Aridisols, which are relatively leached and ae mostly covered by had grass and shrubs while those in Naivasha Oxisols, mostly common in the tropics.

3.2.2 Experimental Design and Treatments

The experiment was laid out in a Split-Plot Design, where fields "with manure" and "without manure" represented the main plot factor. Manure was obtained from the cow shed in livestock units of both KALRO centres. The sub-plot factor was comprised of *Zai* pits of different sizes: Without *Zai* (Z_0) i.e., Flat (which also received manure at a similar rate as *Zai* pitted subplots), *Zai* pits measuring 60 × 60 × 30 cm (Z_{30}), *Zai* pits measuring 60 × 60 × 45 cm (Z_{45}) and *Zai* pits measuring 60 × 60 × 60 cm (Z_{60}). A spacing of 45 cm between *Zai* pits was considered for all the plots. These treatments were replicated four times in both the two study sites.

During the digging of the *Zai* pits, soil from the pits were piled on the side of the pit for the first 50%. This represented the top soil, which was then mixed with 1.2 kg (for Katumani) and 0.6 kg (Naivasha) of Farmyard Manure for each pit, representing application rates of 9.8 t/ha and 4.9 t/ha for the two locations respectively, as recommended after soil fertility analysis of the sample from the respective study locations, followed by cattle manure analysis, which determined their nutrients content. Analysis method were similar to the method described in the "Soil characterization" (below), after which the mixture was returned back into the pits. This was then followed by planting of the Cowpea seeds, where 15 seeds were planted per pit in the pitted plots (containing 12 *Zai* pits) while 3 seeds per hole (in flat plots containing 60 holes). These gave seed density of 120,000 seeds per hectare.

The lower 50% of the soil was piled on the lower sloping side of the pit and was never returned back to the pit. It remained on the side of the pit to reduce the rate of the run-off during precipitation and hence increase the amount of the rainwater collected in the pits.

3.2.3 Soil Characterization

Prior to land preparation, soil samples were taken to the lab for initial characterization. Samples for chemical analysis were collected using Soil auger at equidistant points forming a Zigzag at a depth of 15 cm below the ground surface. These were then mixed in a bucket to form composite samples, after which the representative samples were put in a brown khaki bag

for analysis. The samples were air – dried in an open-air space for 7 days, after which it was sieved using <2mm sieve. Sieving was then preceded by testing different soil parameters. Soil texture was investigated, through carrying out particle size analysis (PSA) using hydrometer method, as outlined by (Gee & Or, 2002; Okalebo *et al.*, 2002). Infiltration rate was measured in situ (Pal 2018) using the Double ring infiltrometer method (Bodhinayake & Cheng, 2004; Lai & Ren, 2007; Swatzendruber & Olson, 1961).

Bulk density was determined by the core ring method, where undisturbed samples were collected by driving core rings into the soil up to a depth of 15 cm using compaction hummer, then the core ring was removed with its content (soil). The extending soils on the core sampler was then trimmed carefully with a knife. This was to ensure that the volume of the soil sample fits or is the same to the volume of the core ring.

At the lab, the core rings were placed in the moisture can and weighed together with its content. The core ring plus its content was then place in an oven and dried at 105°C for 24 hours, to ensure a constant weight was achieved. After drying, the core ring was then weighed, and the dried weighed recorded. Bulk density was then determined by finding the quotient of the mass of solids and the total volume of soil in the core ring (which has a diameter of 5 cm and a height of 5 cm):

$$\text{bulk density of the soil} = \frac{\text{Mass of solids}}{\text{Total volume}} \quad \text{.....equation 3.1}$$

$$\rho_b = \frac{Ms}{Vt} \quad \text{.....equation 3.2}$$

While using the same sample(s), mass of water lost was determined by finding the difference between the initial weight of wet soil and the (final) oven – dried weight of soil. This mass was then converted to volume by using the density of water; 1 gml^{-1} (Mylavarapu, 2002) which was then used to determine the Volumetric water content (Θ) of the soil by dividing volume of lost water by the total volume of soil in the core ring.

$$\text{Volumetric water content} = \frac{Volume\ of\ water}{Total\ Volume} \quad \text{.....equation 3.3}$$

Soil pH (water) was determined by a 1:2.5 soil to water ratio, as described by Okalebo *et al.*, (2002), Nitrogen was determined according to Kjeldahl method (Estefan *et al.*, 2013), Phosphorus, Potassium, Magnesium, Sodium, Manganese and Calcium were determined using Mehlich I (Double acid) method, according to Mylavarapu *et al.* (2002), while available Iron, Copper and Zinc were extracted in a 1:10 ratio (w/v) with 0.1 M HCl, which were later determined using AAS (Atomic Absorption Spectrophotometer). Soil carbon was determined calorimetrically according to Okalebo *et al.* (2002).

Soil moisture was monitored weekly using soil neutron probe, Troxler 4300 model. Here, calibration was first done to enable continuous, steady and accurate measurements specific to soils at each location (Gomez & Gomez, 1984). Readings were taken weekly throughout the growing season at depth intervals 10 cm from 0.1 m up to 1.0 m deep.

Soil classification and characterization (***Table 3.1***) showed that Naivasha had Loamy soils which is well drained, while Katumani had sandy loam soils which is highly drained and very dry at the time of sampling.

Table 3.1: Soil and Manure characterization at Naivasha (Nakuru County) and Katumani (Machakos County) study sites at the beginning of the experiment

Sample	Analysis	Parameter	Unit	Naivasha	Katumani
Soil	Physical	Bulk Density	g cm^{-3}	1.40	1.20
		Infiltration Rate	$cmhr^{-1}$	183.70	253.10
		Volumetric Water content	%	24.10	8.20
	Chemical	Total Organic Carbon	%	2.50	0.70
		pH		6.40	5.80
		Total Nitrogen	%	0.20	0.10
		Total Phosphorus	$mg.kg^{-1}$	284.00	39.50
		Potassium	$cmol.kg^{-1}$	2.80	0.80
		Calcium	$cmol.kg^{-1}$	7.20	1.20
		Magnesium	$cmol.kg^{-1}$	3.80	1.90
		Manganese	$cmol.kg^{-1}$	0.60	0.40
		Sodium	$cmol.kg^{-1}$	1.20	0.20
		Ion	$mgkg^{-1}$	43.70	23.10
		Copper	$mgkg^{-1}$	0.80	2.50
		Zinc	$mgkg^{-1}$	7.10	2.60
Manure	Chemical	pH		7.42	7.38
		Total Nitrogen	%	2.01	1.93
		Total Phosphorus	$mg.kg^{-1}$	0.35	0.29
		Potassium	$cmol.kg^{-1}$	0.51	0.52
		Calcium	$cmol.kg^{-1}$	1.20	7.20
		Magnesium	$cmol.kg^{-1}$	1.90	3.80
		Manganese	$cmol.kg^{-1}$	0.23	0.21
		Ion	$mgkg^{-1}$	2907.00	2856.00
		Copper	$mgkg^{-1}$	632.00	654.00
		Zinc	$mgkg^{-1}$	166.00	163.00

At the end of the experiment, soil was sampled for lab analysis, mainly for extractable phosphorus and inorganic nitrogen. Composite samples were obtained from each of the subplots. They were obtained from each of the *Zai* pits using an auger up to a depth of 20 cm from the surface of the soil (surface vary from one pit to the other depending on the depth of specific pits), and taken through the drying process as described above. Inorganic N was then determined using 2M KCl as extracting solution, using the ratio 1:5 (soil: solution) according to Estefan *et al.* (2013) while extractable P was determined by using 5M sodium bicarbonate ($NaHCO_3$) as the extracting solution (Estefan *et al.*, 2013).

3.3 Data Analysis

The data was first tested for normality using "Proc univariate Normal plot", after which it was subjected to the analysis of variance (ANOVA) using proc GLM in Statistical Analysis Software (SAS) version 9.2 (Mangale *et al.*, 2016), followed by mean separation using Tukey's Honestly Significant Difference (HSD) at $\alpha = 0.05$.

3.4 Results

3.4.1 Changes in selected soil properties as influenced by *Zai* pits and manure application

Difference in soil characteristics were observed at the end of the experiment, with respect to the initial soil characteristics (***Table 3.1***), in terms of soil inorganic nitrogen and soil extractable phosphorus. Similar differences were also observed among plots with different manure levels (main plot factor) and different *Zai* pit sizes (sub – plot factor). Data analysis revealed a significant difference ($P \leq 0.001$) due to location (***Table 3.2***) in inorganic nitrogen (N_{in}) and extractable phosphorus (P_{ex}) in soil samples analysed at the end of the experiment.

Further, mean separation at $P \leq 0.05$ shows that manure application had a significant effect in the level of N_{in} at the end of the experiment. This was also the case when means of P_{ex} were separated ($P \leq 0.05$) (***Table 3.2***). *Zai* pit depth, the sub – plot factor was also significant at $P \leq 0.05$ for the soil N_{in}. Interaction between Manure and *Zai* pit technology significantly ($P \leq 0.05$) affected soil N_{in} as well as soil P_{ex} at $P \leq 0.001$, with higher N_{in} from 45 cm *Zai* Depth in both two sites (***Table 3.3***).

Table 3.2. Soil inorganic N (mg.kg^{-1}) and extractable P (mg.kg^{-1}) under various levels of manure application in the two sites

Location	Inorganic N (mgkg^{-1})			Soil Extractable P (mgkg^{-1})		
	Manure	No manure	*MSD*	Manure	No manure	*MSD*
Naivasha	1.80^{a*}	0.83^{a+}	*0.22*	52.44$^{a\neq}$	41.73$^{a\neq}$	*2.87*
Katumani	1.13^{b*}	0.27^{b+}	*0.24*	98.25$^{b\neq}$	72.56$^{b\neq}$	*8.33*
MSD	*0.34*	*0.26*		*23.76*	*18.45*	

Means with the same letters (within a column) or same symbols (along rows) are not significantly different at $P \leq 0.05$ (MSD represents Minimum Significant difference)

Table 3.3. Mean separation for soil Inorganic Nitrogen from the Interaction of *Zai* depths (cm) and Manure levels from the two study sites

Location	*Zai* depth (cm)	Soil Inorganic N (mgKg^{-1})		MSD
		Manure	No Manure	
Katumani				
	0	1.69^{a*}	0.68^{a+}	0.17
	30	1.77^{a*}	0.94^{b+}	0.32
	45	1.98^{b*}	0.95^{b+}	0.14
	60	1.78^{a*}	0.76^{a+}	0.10
	MSD	*0.11*	*0.12*	
Naivasha				
	0	1.08^{a*}	0.20^{a+}	0.20
	30	0.95^{a*}	0.43^{b+}	0.29
	45	1.51^{b*}	0.23^{a+}	0.12
	60	0.98^{a*}	0.23^{a+}	0.04
	MSD	*0.22*	*0.09*	

Means with the same letters (within a column) or same symbols (along rows) are not significantly different at $P \leq 0.05$ (MSD represents Minimum Significant difference)

In the experiment, there was a significant improvement in the soil chemical parameters. Inorganic Nitrogen (N_{in}) level in the soil was increased from 0.23% at onset of the experiment to an overall mean of 0.69% at the end of the experiment while total phosphorus (P_{ex}) increased by 29.9% in Naivasha soils. In Katumani, an upward trend was observed, with an increase of 62.5% in N_{in} and 19.4% in P_{ex}. Soil analysis also revealed a significant difference in manure

treatments. Plots with manure application revealed a tremendous alteration in soil chemical parameters, e.g., in ***Table 3.3,*** N_{in} was constantly higher and significantly different between plots that were applied with manure and those plots that had "No Manure" application, this trend was observed in both Katumani and Naivasha study sites.

3.4.2 Cowpea growth responses to *Zai* pits and manure application

Cowpea height and stem diameter were measured 14, 35, 56 and 70 Days after planting (DAP). Running ANOVA revealed that stem diameter and plant height differed significantly ($P \leq 0.001$) across sites (***Figure 3.2***), with Naivasha producing both the highest mean pant height of 32.9 cm as well as the largest stem diameter of 0.51 cm. It is also worth noting that plant heights from Naivasha were all higher than those from Katumani, as observed in ***Figure 3.2,*** where all the heights from Naivasha are above the horizontal line. It was also noted that manure application on both sites influenced cowpeas stem diameter, since the mean diameter (***Figure 3.2***) in Katumani was high, at 51.51% compared to Naivasha, with mean separation using Tukey's HSD revealing a significant difference at $P \leq 0.05$. ANOVA also revealed a significant difference of mean plant height at $P \leq 0.01$ due to manure application.

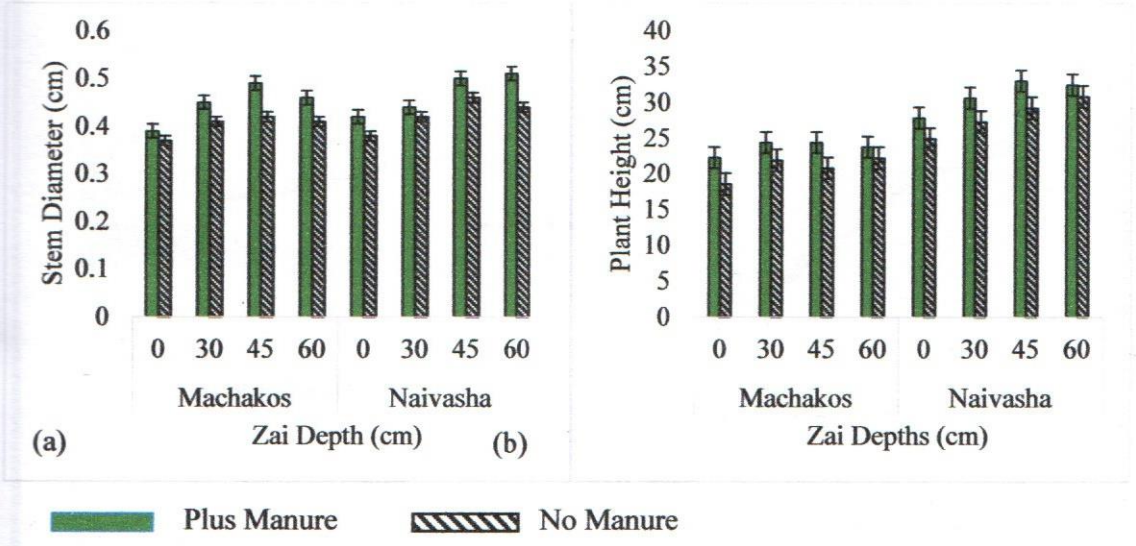


Figure 3.2*: Zai pits and manure interaction effect on stem diameter (cm) (a) and plant height (cm) (b) of cowpea in two study sites (Bars with overlapping standard deviation error bars are not significantly different at $P \leq 0.05$)*

Cowpea stem diameter varied with *Zai* depth significantly ($P \leq 0.001$) (***Figure 3.2***) while an interaction between Manure application and *Zai* pit technology had significant effect in plant height at $P \leq 0.05$. Mean square comparison using Tukey at $P \leq 0.05$ also revealed that

there was significant difference between *Zai* pit depths on mean stem diameter, with 45 cm and 60 cm depths producing the largest diameter while 0 cm (flat) and 30 cm depths producing smallest diameters. Difference was also observed with respect to location, where plants from Naivasha site were significantly taller (***Figure 3.2***) than those from Katumani. ANOVA at the same time revealed that time (DAP) of measurement had an effect on the stem diameters (***Figure 3.3a, c***) and plant heights (***Figure 3.3b, d***), noting that there was a continuously upward trend in growth and development of the crops through time.

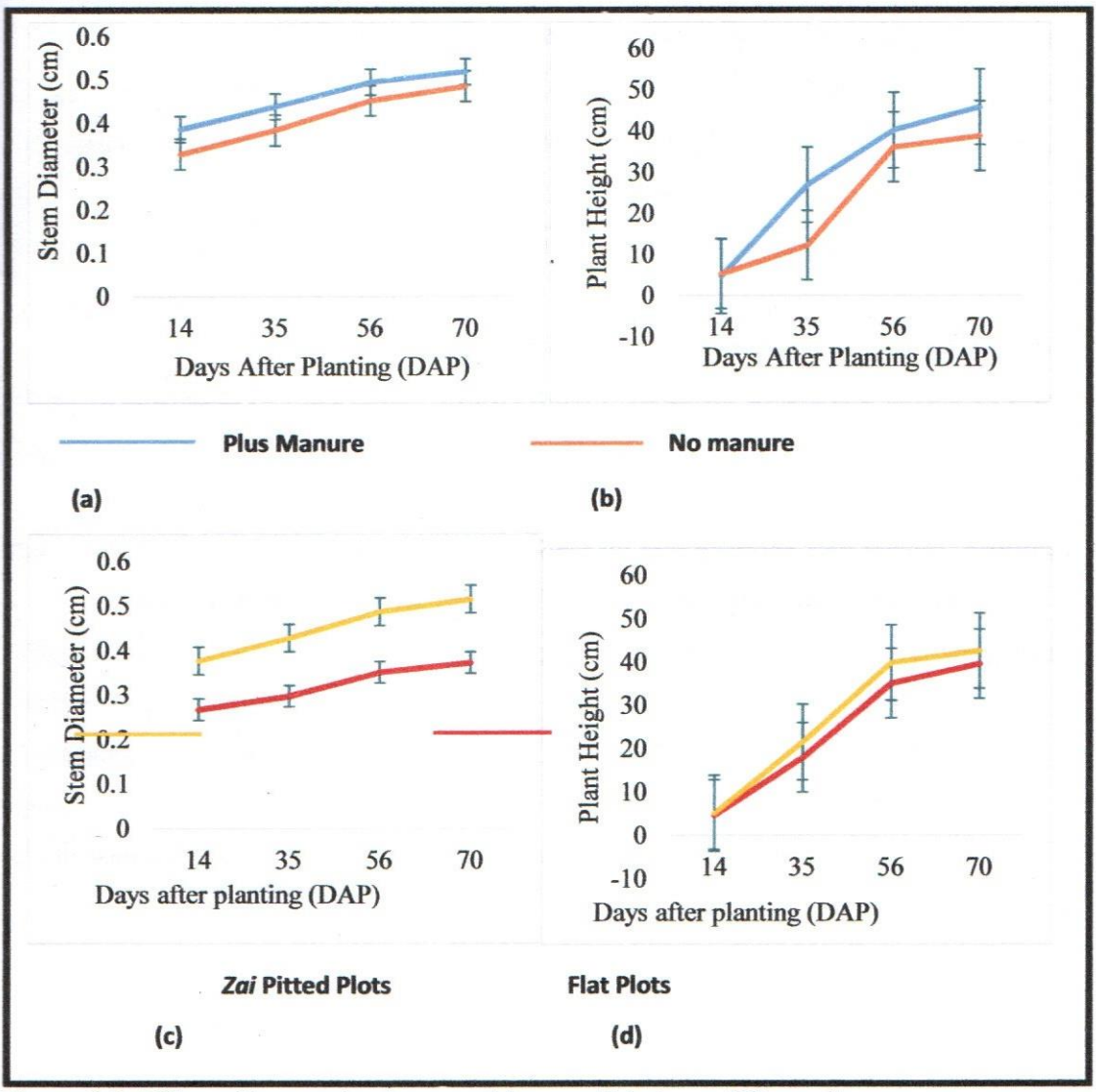


***Figure 3.3**: Effect of interaction between Manure, Zai pits and Time of measurement on stem diameter (cm) (a, c) and plant height (cm) (b, d) of cowpea*

Plant tissue analysis revealed influence of nutrients in the tissues by the applied treatments. Close observation of ***Table 3.4*** reveals that location significantly ($P \leq 0.001$) influenced both total nitrogen (N_T) and total phosphorus (P_T). Manure application also had a

significant effect on both N_T and P_T (***Table 3.4***) from the analysis of plant tissues. Further, ANOVA shows that an interaction between location and manure significantly influenced total nitrogen in the plant tissues, based on comparison of means between crops that received manure and crops that had "No Manure" application.

Table 3.4. Total N (%) and total P (%) in plant tissues as influenced by manure application across locations

Location	Plant total N (%)			Plant total P (%)		
	Manure	No manure	*MSD*	Manure	No manure	*MSD*
Katumani	3.46^{a}	3.24^{c}	*0.17*	0.31^{e}	0.28^{g}	*0.02*
Naivasha	3.77^{b}	3.34^{d}	*0.09*	0.25^{f}	0.27^{h}	*0.02*
MSD	*0.14*	*0.06*		*0.01*	*0.01*	

Means with the same letter(s) within a column are not significantly different at $P \leq 0.05$

Furthermore, ANOVA revealed a significant difference in the number of pods and pod weight of cowpea at $P \leq 0.001$ and 100 seed weight and stover weight at $P \leq 0.05$. (***Table 3.5***), which were greatly influenced by manure application.

Table 3.5. Farmyard manure application effect on pod number, pod weight, hundred seed weight and stover weight of Cowpea from the two study sites

Manure level	Pod number	Pod weight (g)	100 seed weight (g)	Stover weight (g)
With Manure	10.65^{a}	17.73^{b}	12.25^{b}	33.82^{a}
No Manure	8.31^{b}	22.39^{a}	12.63^{a}	26.75^{b}
MSD	0.91	2.15	0.33	5.70

Means with the same letter within a column are not significantly different at $P \leq 0.05$

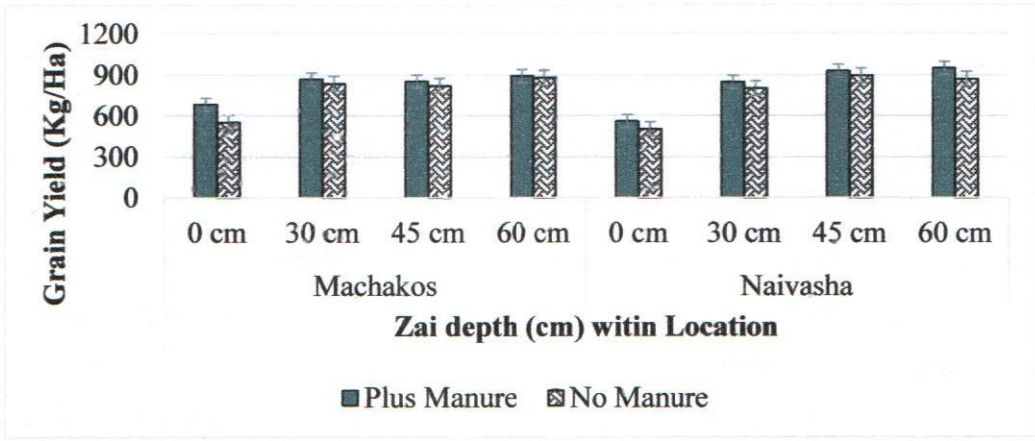


Figure 3.4: *Zai pits depth (cm) and Farmyard Manure Interaction effects on cowpea grain yields from the two study sites (Bars with overlapping standard deviation error bars are not significantly different at $P \leq 0.05$).*

Zai depth, the sub – plot factor influenced the final yields (***Figure 3.4***), since it revealed significance at $P \leq 0.001$ while an interaction between Manure (Main plot factor) and *Zai* depth (Sub – plot factor) influenced 100 seed weight ($P \leq 0.001$) as well as the stover weight at $P \leq 0.05$. Flat plots produced low grain yields from both the two sites (***Table 3.5***), revealing the great roles played by the *Zai* pits in growth, development and final yield of Cowpea.

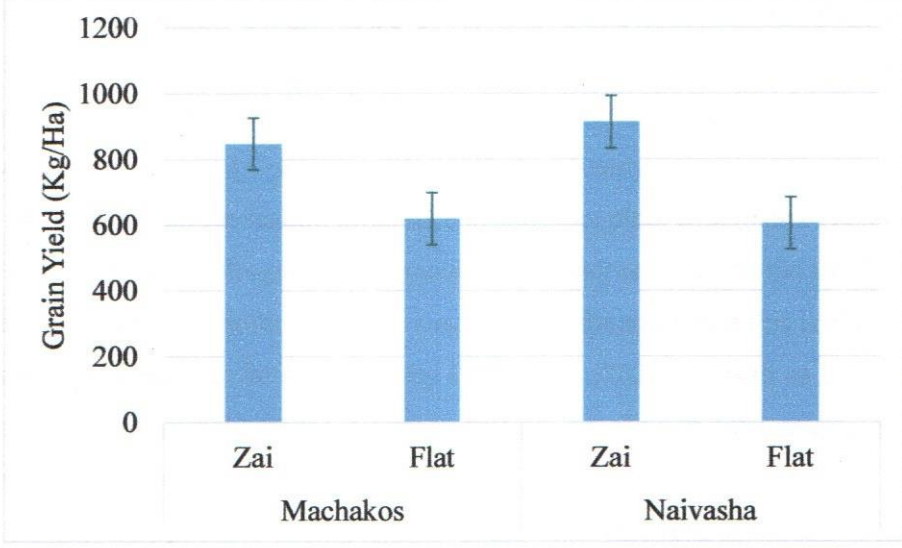


Figure 3.5*: Grain yield variation as influenced by Zai pits versus Flat plots in both* Katumani *and Nakuru Sites*

3.5 Discussion

Improvement in soil nutrient status can be attributed to the effect brought about by addition of manure, which after decomposition, released nutrients in available forms like

ammonium ion (NH_4^+), Nitrite ion (NO_2^-) and Nitrate ions (NO_3^-) that are available for plant uptake (Beck *et al.*, 2004). Secondly, presence of enough soil moisture in the soil (after collection in *Zai* pits) that dissolve plant nutrients from complex solid substances which existed in the soil to ionic inorganic forms that can be detected and up-taken by plants (Akhtar *et al.*, 2020).

In the present study, manure application to the soil may have improved soil particle aggregation that might improve water infiltration in the soil. *Zai* pits acted as a trough, which trapped the infiltrating water, thereby reducing percolation hence making the water remain within the rooting depth of the crops (Cowpea). This can be affirmed by the results of Adeyemo *et al.* (2019) and reinstated by Kausar *et al.* (2020) that, combining *Zai* pits and manure application improved the soil water retention, providing enough moisture for plant growth.

Significant difference in inorganic nitrogen and extractable phosphorus in the two locations can be attributed to the difference in the rainfall occurrence in the two locations. Given that the two locations are situated within similar agroecological zones (AEZ IV), climate change over time has resulted in slight difference in weather conditions hence varying rainfall received (Kimaru – Muchai *et al.*, 2020). This then explains the difference in soil moisture content that resulted into difference in decomposition rates of the applied manure hence the difference in nutrient contents. The higher extractable phosphorus in Naivasha can be attributed to the fact that humid conditions (locations) facilitate rate of decomposition and release of nutrients. Therefore, the rate of release of P into soil solution for plant utilization was higher in Naivasha site compared to Katumani in Machakos county.

Mean separation revealing difference in soil from plots with manure application having higher mean inorganic nitrogen and extractible phosphorus is due to the fact that addition of manure is equivalent to addition of more nutrients into the soil hence this enriches the soil with plant nutrients. These can be supported by Chen *et al.* (2020), as well as Deng *et al.*, (2020) who observed that animal manure is a renewable source of plant nutrient elements such as N, P, K and other macronutrients.

Zai pits also influenced soil N_{in} and P_{ex} that were analysed at the end of the study, with different *Zai* pit depths recording different levels of inorganic N. *Zai* pits at 45 cm depth recorded highest mean N_{in} while flat plots gave the least N_{in}. This is attributed to the fact that flat plots lacked enough soil water, therefore inadequate soil moisture that reduced the decomposition rate. Incomplete decomposition of the FYM manures limits the nutrients release hence limiting the amount of nutrients for plant uptake. Deeper pits (60 cm) recorded relatively lower soil N_{in}. This may be due to the fact that collected water was too much such that during

infiltration and deep percolation, leaching occurred, hence taking the plant nutrients deep beyond the root zone. This finding can be supported by Luo *et al.* (2020) who stated that high water accumulations prompts water-logging and might result in plant nutrient leaching. Since water logging was observed in some *Zai* pits in the Naivasha field, this must be true. Low Nin at the 60 cm *Zai* depth can also be attributed to the fact that plant nutrients tend to reduce with increase in depth, making the lower soil horizons be deficient in plant essential nutrients.

Essential nutrients elements available in the soil in the rightful amounts prompts healthy growth and development of the crops. Nutrients uptake by plants is a continuous process that takes place when the nutrients are in the right forms. Nourishment of crops is key for growth and maximum yields. To determine the amount of nutrients in the plant tissues, sampling is done at the right time, for instance in this study, cowpeas tissue samples were done at 45 DAP, just few days before flowering (Cataldo *et al.*, 1974; Lopez – Calderon *et al.*, 2020). Tissue analysis for total nitrogen and total phosphorus revealed varying significant levels. Significance due to location effect can be attributed to difference in mineralization processes in the two locations (Lopez – Calderon *et al.*, 2020). The lower Katumani N_T might have been affected by leaching of nutrients from soil (in form of N_{in}) due to soil textural composition, since it has higher percentage sand compared to the proportions of silt and clay. This makes the soil in Katumani more porous with higher infiltration rate as well as higher percolation rate, therefore as water moves the lover layers, it carries plant nutrients with it (Beiyuan, 2020; Gopal 2019;), therefore only few amounts (nutrients) remain in the soil for plant uptake that relatively lowered the tissue N_T.

Total N and P are significantly affected by manure application into the soils, in that soils where manure is added reflect a great amount in plant tissues (Heifner *et al.*, 2020). This is attributed to the fact that after decomposition, the added manure release plant nutrients into the soil, which plus on top of the nutrients that were already in soil initially, hence during uptake, a significant amount are utilized by the crop (Kong *et al.*, 2020), compared to crops from plots that were not supplied with manure. In some plots where N_T was high, it was noticed that there was a corresponding higher level of P_T. This is better explained by the findings by Hefner *et al.* (2020) who stated that synergies exist on the uptake process of some plant nutrient, hence N facilitated uptake and utilization of P (an immobile nutrient) up to a certain extent.

Greatly affected are the stem diameters and plant height of cowpeas, resulting in their variation across different treatments. Plants growing under adequate water supply and available nutrient elements in the right amounts are bound to grow healthily and provide highest yields. Soils with higher soil N_{in} and P_{ex} among other elements boosted the stem diameter and height

this explains the significance among observations from plots treated with manure and those where manure was not applied.

Water is critical in various development stages of plants. Various *Zai* pit depths provided different moisture levels to plants, hence varying plant diameters. Larger stem diameter was observed in deeper *Zai* pits which stored higher moisture content than in shallow and Flat plots. This can be explained by findings by Kong *et al.* (2020) who stated that stem diameter has a strong correlation with available plant moisture, up to a certain point, just before water-logging that affects "normal" crops' growth and development.

Tentatively, Wan *et al.* (2020), states that xylem and phloem of growing crops increases in size continuously with time, provided that all the growth (both soil and weather conditions) factors are optimal for growth, up to the maximum depending on the crop grown as well as its genetic traits. This explain why the means observed show continuous increase in diameter and height of cowpea from 14 days after planting (DAP) through to after 70 DAP, after which lateral growth in branches was observed. Continuous enlargement in diameter can also be explained by the fact that *Zai* pits continuously accumulated water hence plants had high chances of converting the provided water into biomass (Water use efficiency) with respect to time.

Results from plots treated with manure application showed a continuously higher mean values in number of pods, 100 seeds weight and stover weight at harvest. This shows that manure resulted in a significant alteration in plants nutrients, and coupled by its effect on soil moisture, crop performance can be enhanced a great deal (Uddin *et al.*, 2020). This can also be explained by the findings of Astiko *et al.* (2020) that supplying crops with adequate water as well as plant nutrients favours absorption and utilization of the water and plant nutrients which accelerates development of generative organs like branches and higher number of pods which in turn boosts the 100 seeds weigh and the final stover weight at harvest.

The variation in yield data indicate that any change in moisture levels in soil is proportionally reciprocated by plant performance. Manure contains plant nutrients, hence on decomposition, macronutrients like nitrogen and phosphorus are made available for plant uptake. Nitrogen is present in different forms. The inorganic form of N, i.e. Ammonium-N (NH_4^+) is immediately available to plants after a short while of application. Therefore, manure influenced plant performance in terms of yield. Same conclusion was also drawn by Goldberg *et al.* (2020) who achieved positive results on short term effects of livestock manure on soil properties. Conditions for better performance were also created by enough soil moisture

content which was a result of collection by *Zai* pits. An interaction of the two led to higher 100 seeds weight as well as stover weight at harvest.

3.6 Conclusion

To increase productivity on the current scarce and low agriculturally productive lands especially in dryland areas, investing in better agricultural inputs and technologies is key. Use of *Zai* pit technology is one of the interventions that has been proven by this research to improve soil N and P content, which in turn improved cowpea growth parameters such as stem diameters and height and grain yield. Varying *Zai* pit depths depending on location and combining it with Farmyard manure guarantees quantity of cowpea by enhanced yields. By using this technology, food insecurity in the ASAL rural areas of Kenya, which are occupied mainly by smallholder farmers, can be eradicated.

3.7 Recommendation

Since ASAL areas experience erratic rainfall regimes, when using *Zai* pits in the farms, the size of the pits matters a lot. Findings from this research has proven that a pit with 45 cm depth performs better in terms of moisture retention as well as on plant nutrient delivery, that has seen an increase in stem diameter, height and higher final yields. It is also important to point out that soil moisture boosts yield and general productivity up to a certain level, beyond which no difference is observed. This is evident in Naivasha where pits with 60 cm depth produced least yields. They could store water for longer, till they become waterlogged for a period of time. Combining *Zai* pit technology with manure application guarantees highest yields since they provide nutrients, which is evident by improved inorganic nitrogen and extractable phosphorus in soils, well as improving soil structure that aid in boosting soil moisture availability at the root zone. These in turn brought about higher N_T and P_T in cowpeas tissues thereby contributing to significance in yields from plots that contained *Zai* pit technology. We also recommend that this research should be carried out over more than two seasons to assess how often manure should be added based on duration of residual effect of the applied manure.

CHAPTER FOUR

SOIL MOISTURE DYNAMICS AND WATER USE EFFICIENCY OF COWPEAS (*Vigna unguiculata* L. WALP) UNDER *ZAI* PIT TECHNOLOGY (*TUMBUKIZA*) IN ASAL LOCALITIES

Abstract

Low crop yields in Arid and Semi – Arid lands (ASALs) is usually associated with low soil moisture resulting from low and erratic rainfall. These soils tend to lose water faster through infiltration and deep percolation leaving top soil dry, which lowers yield. Low yields result from low Water use efficiency (WUE) of crops. *Zai* pits collect rainwater and avails it to crop, thereby availing nutrients in the required forms for utilization by plants. The aim of this study was to determine how a combination of *Zai* pit technology and manure alters soil moisture content and the degree to which they affect water use efficiency of cowpeas. In this study, *Zai* pits of varying depths (Flat -Z_0, 30 cm – Z_{30}, 45 cm – Z_{45} and 60 cm – Z_{60}) were used in combination with two manure levels (0 and 2t Ha^{-1}) across two locations falling under similar Agro-ecological zone IV (AEZ IV). These were put in split plot arrangement with Manure levels as main plot factors while *Zai* treatment as sub plot factors. Volumetric moisture content was measured using Neutron Probe weekly for 16 weeks at depths of 10cm, 20cm, 30cm, 40cm, 50cm, 60cm, 80cm and 100cm successively, while WUE was computed after harvesting. The data was analysed using proc glm in SAS version 9.2. The treatments were compared to performance of flat plots where *Zai* pit technology was not applied. Soil volumetric content followed the trend: $Z_{45} > Z_{60} > Z_{30} > Z_0$ at 25.3 %, 23.9%, 23.7% and finally 20.3% respectively. There was significant difference in water use efficiency of crops (cowpeas) among the different *Zai* pit depths Further, combining *Zai* pits with manure helps in bettering crop performance by boosting WUE, making it higher in plots treated with manure (mean of 12.52 $kg.Ha^{-1}mm^{-1}$) than in plots without manure mean of 9.8 $kg.Ha^{-1}mm^{-1}$. According to the data, it can be concluded that *Zai* pit technology improves soil moisture status, which if combined with manure application, leads to better crop performance as depicted by high WUE in plots that had combination of *Zai* pit technology and Manure.

Key words: Moisture Dynamics, *Zai* pits, Water use efficiency, Cowpea, ASAL, Drought,

4.1 Introduction

Erratic rainfall and prolonged drought, coupled with infertile soils are among the limitations of rainfed agriculture in dryland areas (Ahmed *et al.*, 2020). Farmers in the Sub – Saharan Africa (SSA) are faced with challenges of low yields every season since they depend

on rainfall for their crop production, but due to climate change, reduction in rainfall occurrence and low amounts leads to frustration of many farmers who are fully dependent on rainfed agriculture (Bari, 2017). Kenya experiences similar challenges (Kimaru – Muchai *et al.*, 2020) in its North – Eastern and Eastern regions (as well as some parts of Rift Valley like Marigat, Lari and Naivasha) which are classified as Arid and Semi – Arid Lands (ASALs).

There is an upwards trend in population change from comparison between 2009 and 2019 population census by Kenya National Bureau of Statistics (KNBS 2019), hence something needs to be done to minimize the food insecurity in the near future, mainly in ASAL areas where the low yields are attributed to low soil (water) moisture. Actions and strategies need to be devised to take care of the soil moisture problems in the soils of these regions like the use of *Zai* pit technology which makes it easier to concentrate rain water at the root zone for plants utilization. Availing enough water for plant utilization guarantees a promising harvest, hence enough food to take care of the ever – increasing population.

Zai pit technology is the use of pits strategically and systematically dug in the farm, specifically designed to aid in rain water harvesting as well as availing the water exactly at the plant roots for uptake (Kimaru-Muchai *et al.*, 2020). Most soil types, especially the Aridisols found in arid areas have the tendency to lose gravitational and capillary water very rapidly, making them very dry shortly after rainfall occurrence (Kathuli & Itabari, 2015). *Zai* pit technology aims at trapping these categories of water and making use of it before it percolates deep underground. It will therefore provide enough additional water for plant utilization, hence increase in plant biomass (Farias *et al.*, 2017; Mganga *et al.*, 2019). During preparation of *Zai* pits, the top soil from the pits is mixed with any soil amendment intended and returned back to the pits while the lower half of the soil is piled on top lower slope next to the pit to help trap rain water in case of runoffs.

Various soil amendments can be used in combination with *Zai* pit technology. Both organic and inorganic works well, but as Kimaru-Muchai *et al.* (2020) found out, the technology is got conservation agriculture, trying to reclaim the weathered soils of arid areas, therefore, organic amendments like manure are therein recommended. Manure and the collected water in the pits have the tendency to collectively improve soil physical and chemical characteristics (Eghball, 1999). Structure is improved by manure that initiates aggregation process of the soil colloids (Lal & Shukla, 2015). This increases the colloidal specific surface area of soil particles hence large number of nutrient ions can be adsorbed to these surfaces (Sposito, 2008). These ions, upon dissolution in the water (availed by the pits), are available for plant uptake, hence nourishment and finally higher yields are obtained (Diagboya *et al.*,

2015). Nutrients being adsorbed at these surfaces come partly from the soil i.e., the reserves that were not available to plants due to moisture stress in the dry soils, while close to 75% (Kimaru – Muchai *et al.*, 2020) come from the manure that is added. Manure has the ability to supply various, both macro- and micro – nutrient elements which are essential in plants life circle.

Manure is a good supplier of micronutrients like copper (Cu), manganese (Mn) and zinc (Zn) while the major macronutrients supplied are Nitrogen (N), Phosphorus (P) and Potassium (K) and are essential in plants growth and development (Mangale *et al.*, 2016). Nitrogen is a component of chlorophyll, component of amino acids and a building block of proteins (Paul 2007). N is available to crops in inorganic forms i.e., NH_4^+ and NO_3^-. Phosphorus is immobile nutrient in soil, but a little change in pH in the surrounding environment makes it available to crops for uptake. It is utilized by plants in its oxide forms, that is, orthophosphates (HPO_4^{-2}, $H_2PO_4^-$) (Mangale *et al.*, 2016). P boosts plants' immunity against diseases as well as increase in the quality of flowers and fruits.

Legumes' ability to fix nitrogen makes its production economical since less soil amendments are needed. Fertilizer and manure should be minimized since excess of nutrients like N and P can lead to burning of crops hence reducing yield. This might prove uneconomical. Different legumes can fix varying amounts of N, when managed right (Aiosa *et al.*, 2020). Studies show that Cowpea (*Vigna unguiculata*) can fix approximately 99.76 kg/ha of N (Mangale *et al.*, 2016), hence little amount of manure is needed in its production. This can e a real advantage to the rural Sub Saharan communities who can embark on Cowpeas production to supplement their daily foods. Research have proven that cowpeas is nutritious in human body since it contains proteins and minerals (Nascimento *et al.*, 2020). Its production in ASAL areas is limited due to drought, but use of t right variety that can tolerate moisture stress as well as utilization of *Zai* pit technology, higher yields can be achieved and water use efficiency will sure be high due to production of healthy crops (Belay & Fiseha, 2020).

The ability of crops to convert water from the soil into biomass (Wang *et al.*, 2020) is the Water use efficiency of crops (Bari, 2017). Availing adequate water to the crops and prolonging its (availability) stay at the root zone encourages water utilization (Omori *et al.*, 2020, Wang *et al.*, 2018), hence higher biomass is achieved, that lead to great harvest. There exist studies on *Zai* pits, but little is documented on their effect on water use efficiency, especially while using cowpeas as the test crop. Its effect on soil moisture dynamics, especially as depth of measurement increases is also minimal. This study therefore had an aim of

determining the combined effect of *Zai* pit technology and manure on water us efficiency of cowpeas in the dryland areas of Kenya.

4.2 Materials and Methods

The experiment was carried out in two different locations, falling under similar Agro-ecological zone i.e., zone IV which is categorized as semi-arid regions. These included Naivasha in Nakuru County (Latitude -0.708, Longitude 36.375) with an annual rainfall of 1291.4 and daily average temperatures of 18.5°C and Katumani in Machakos County (Latitude -1.582, Longitude 37.243) with an annual rainfall of 801.3 and daily average temperatures of 12.2°C.

Zai pits were prepared a month early before planting. They were of same surface sizes (60 cm by 60 cm) but of different depths (30 cm deep, 45 cm deep and 60 cm deep). Results from these *Zai* pitted plots were compared to results from flat plots, which represented the farmers' practice. Since the field was laid out in split plot arrangement, the *Zai* pits depths formed the sub plot factors while manure levels, which were in two levels either with (4.94 t/Ha in KALRO Naivasha site while 99.88 t/Ha in KALRO Katumani) or without manure, formed main to factors. Each plot measured 3 m by 5 m while each of these plots contained 12 *Zai* pits. Four replications were used in each site.

For the purposes of the Soil moisture that was measured weekly, 32 polyvinyl chloride (PVC) pipes measuring 120 cm long and 5.08 cm in diameter were installed in each of the two site, i.e. one pipe per sub – plot. During installation, the holes were drilled using soil auger in the one of the middle *Zai* pits in the sub plots. The pipes were locked in both ends, after which 100 cm of t pipe was dipped into the drilled hole while 20 cm was left on top to aid in holding the Neutron Probe.

Before soil measurement, the probe was first calibrated (Ward & Wittman, 2009) in both the two sites to ensure accurate results. Calibration was done at intervals of 10 cm up to 1-meter-deep into the ground. First, a standard count was taken, then field counts were taken then recorded alongside corresponding volumetric water content given by the probe. To find the count ratios, field counts were divided by the standard counts.

$$\text{Count Ratio (CR)} = \frac{Field\ Count}{Standard\ Count} \quad \text{.....equation 4. 1}$$

Volumetric water content that was recorded from the probe were plotted against the count ratios to come up with a calibration curve for each site. The generated curves finally gave the following calibration equations for each site:

Katumani in Katumani county $y = 71.916x - 47.139$..... *equation 4.2.*

Naivasha in Nakuru county $y = 87.967x - 45.398$ .....*equation 4.3.*

Where y = volumetric water content

x => Count Ratio (CR)

After probe calibration, planting was done. Cowpea variety M66 was the test crop in this study. This variety was developed by KALRO, and was selected due to its adaptability to dry condition and its ability to resist long droughts. During planting, each of the 12 *Zai* pits (which were spaced at 45 cm from each other) per plot had 15 seeds, three at each of the four corners and three at the middle of the pit. Flat plots contained 60 planting holes, in which 3 seed were planted. At first weeding, thinning was done where 5 plants were thinned from each *Zai* pit while one plant was thinned from each of the 60 planting holes in flat plots. After thinning, all sublots, be it *Zai* pitted or flat ones had a total of 120 plants

On the first week of planting, volumetric moisture data was recorded from each sub pots weekly at depth of 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 80 cm and 100 cm respectively. This was done for both two sites for 16 weeks.



***Figure 4.1**: Installed access tube*

Calculation of water use efficiency (WUE) requires determination of Total Dry Weight (TDW) of plant. This was determined at plant harvest, where plants were uprooted first, then roots separated from the shoot at the root collar. The shoots were then weighed using a portable weighing scale with a maximum weight of 5 kg and an accuracy of 0.1 g. Since WUE is the quotient of TDW and Evapotranspiration (ET),

$WUE = \frac{TDW}{ET}$ ($kgHa^{-1}mm^{-1}$). .....*equation 4.4*

Where WUE is water use efficiency, TDW is the total dry weight and ET is the crop evapotranspiration.

The reference ET was also determined using Penman – Monteith equation(Córdova *et al.*, 2015; Francois, 2009), which involved substitution of climate data into the equation;

$$\lambda ET = \frac{\Delta(Rn - G) + \rho acp\frac{(es - ea)}{ra}}{\Delta + \gamma(1 + \frac{rs}{ra})} \quad \text{.....equation 4. 5}$$

Rn net radiation [W m^{-2}], G soil heat flux [W m^{-2}], ρ_a is air density [kg m^{-3}], c_p specific heat of dry air [J kg^{-1} K^{-1}], e_a actual vapour pressure of the air [P_a], es saturated vapour pressure [P_a], Δ slope of the saturation vapour pressure vs. temperature curve [P_a K^{-1}], γ psychrometric constant [Pa K^{-1}] r_s bulk surface resistance and r_a aerodynamic resistance [s m^{-1}].

The climate data were obtained from weather recording stations situated few Meters way from the experimental plot within the KALRO research stations (Naivasha and Machakos – Katumani) where the experiment was being carried out. Climatic data utilized specifically by this equation included minimum and maximum temperature, minimum and maximum relative humidity, wind speed and height of measurement and sunshine duration. These were entered into the FAO's *Drainage and Irrigation Paper No. 56 excel spreadsheet formula* developed by Francois (2009). This then gave values of (Slope of vapour pressure curve, Net radiation, Psychrometric constant, Wind speed at 2 Meters height and Saturation Vapour pressure deficit) which are substituted to the equation (***equation 6***) to determine the Reference Evapotranspiration (ET_o).

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma\frac{900}{T+273}U2(es - ea)}{\Delta + \gamma(1 + 0.34\,U2)} \quad \text{.....equation 4.6}$$

Where: $\mathbf{T_o}$ reference evapotranspiration [mm day^{-1}], $\mathbf{R_n}$ net radiation at the crop surface [MJ m^{-2} day^{-1}], **G** soil heat flux density [MJ m^{-2} day^{-1}], **T** mean daily air temperature at 2 m height [°C], $\mathbf{u_2}$ wind speed at 2 m height [m s^{-1}], $\mathbf{e_s}$ saturation vapour pressure [kPa], $\mathbf{e_a}$ actual vapour pressure [kPa], $\mathbf{e_s}$ - e_a saturation vapour pressure deficit [kPa], **D** slope vapour pressure curve [kPa $°C^{-1}$], **g** psychrometric constant [kPa $°C^{-1}$].

The necessity of crop evapotranspiration prompted the use of FAO recommended crop coefficient (Kc) for cowpeas in the sub – tropics in the derivation of crop evapotranspiration (ETc) as below:

$ETc = Kc \times ETo$ .....*equation 4.7*

Yield was also determined and computed into kilograms per hectare (kg Ha^{-1}). All these data from the two locations were subjected to analysis of variance (ANOVA) using Statistical Analysis Software (SAS) package version 9.2, after which means were separated using Tukey's Honestly Significant Difference (HSD).

4.3 Results

4.3.1 Influence of *Zai* Pit Technology and Manure Application on Soil Moisture

Moisture content responded to varying *Zai* pit sizes differently. First, mean separation (Tukey) at $P \leq 0.05$ showed significant differences in moisture recorded from different *Zai* pit sizes (***Tables 1)***, with Z_{45} recording a higher mean moisture of 19.11% in Katumani and 31.57% in Naivasha compared to low moisture recorded in Z_0, Z_{30} and Z_{60} from both sites. This is also evident in (***Figure 4.2***) where there is no overlapping of the standard deviation error bars of Z_{45}. Across all the 15 weeks while the error bars of Z_0, Z_{30} and Z_{60} are overlapping across all the weeks.

Table 4.1: Variations of Volumetric soil moisture content (%) and Water use efficiency (WUE) under varying *Zai* pit depths (cm) in Different Locations.

Zai depth (cm)	Moisture (%)		Water use efficiency ($KgHa^{-1}mm^{-1}$)	
	Katumani	Naivasha	Katumani	Naivasha
0	17.78[c]	28.71[c]	7.38d	8.14c
30	18.23[b]	29.18[b]	13.13b	8.51b
45	19.11[a]	31.57[a]	14.59a	9.75a
60	18.24[b]	29.51[b]	11.30c	8.71b
MSD	0.09	0.42	1.32	0.29

Means with the same letter within a column are not significantly different at $P \leq 0.05$

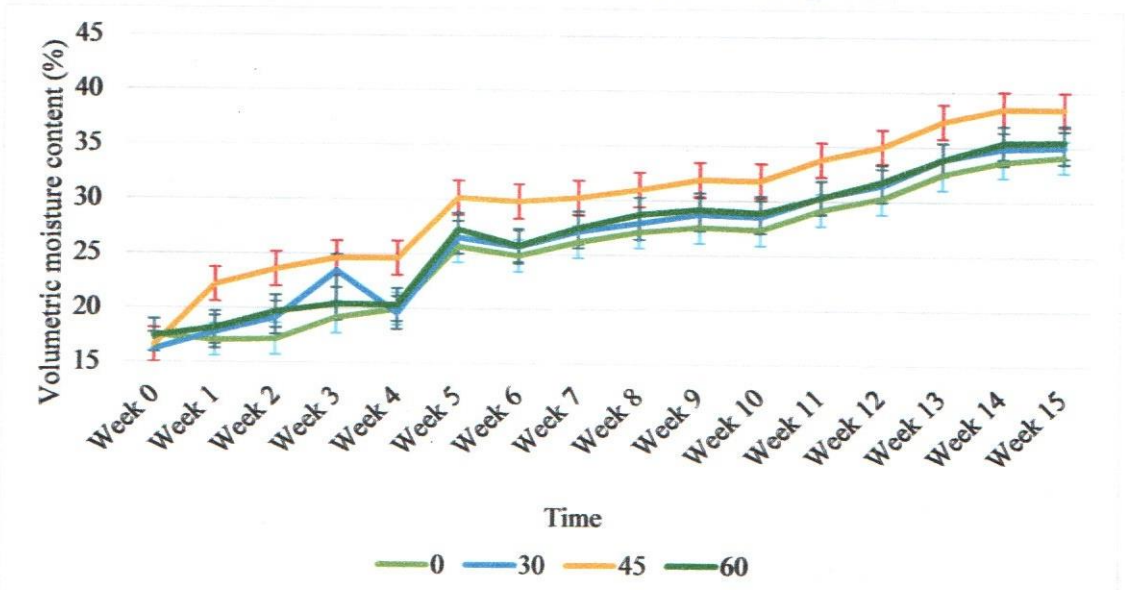


Figure 4.2: *Soil moisture Variation within Zai Treatments over Time (Bars with overlapping standard deviation error bar are not significantly different at $P \leq 0.05$)*

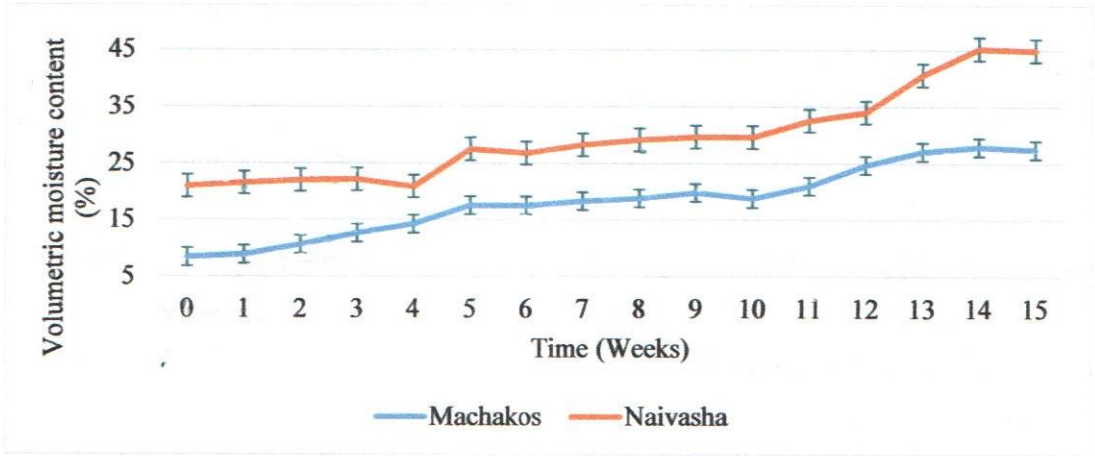


Figure 4.3: *Soil moisture Variation over Time (Weeks) from Katumani and Naivasha study sites (Bars with overlapping standard deviation error bar are not significantly different at P ≤ 0.05)*

There were significant differences in soil moisture content measured in the two locations (***Table 4.1*** *and* ***Figure 4.3***), which are Katumani and Naivasha. This is evident by significance (P ≤ 0.001) of location effect from ANOVA. The moisture data were collected weekly and there was significant variation in the weekly data with respect to location and *Zai* depth (***Figure 4.4***). This was observed throughout all the 15 weeks of data collection (***Figure 4.2*** *and* ***Figure 4.3***).

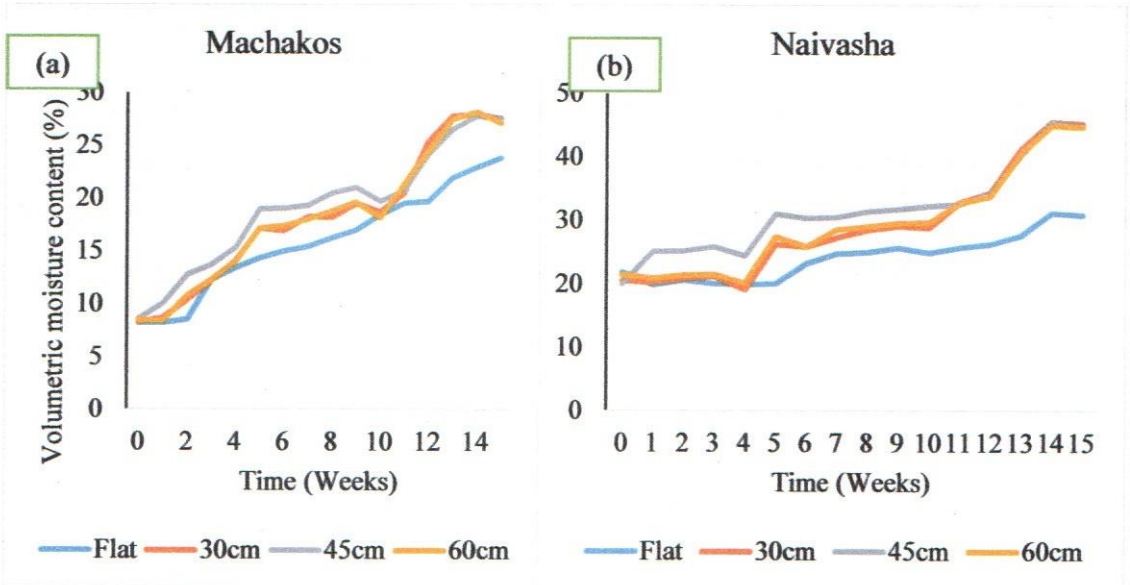


Figure 4.4*: Volumetric soil moisture content (%) variations as influenced by Time in Weeks and Zai Depth as per the Study site.*

Manure contributed to the variation of the moisture content of the soils in the site. It was applied at two levels as main plot factors. Means separation using Turkey at P ≤ 0.05

showed significant performance in the plots "with" manure compared to those plots "without" manure (where it was not applied) (***Table 4.2***). Plots where manure was applied had higher moisture content compared to the plots where there was no manure application, and the trend was observed throughout the 15 weeks in which data was collected.

Table 4.2: Combined Effect of *Zai* Pit Technology and Manure Application Levels on Volumetric Soil Moisture Content (%) and Water Use Efficiency

Zai depth (cm)	Moisture (%)			Water use efficiency ($KgHa^{-1}mm^{-1}$)		
	With Manure	Without manure	*MSD*	With Manure	Without Manure	*MSD*
0	28.71^{c+}	17.78^{c*}	*2.14*	$7.64^{c\neq}$	$7.87^{b\neq}$	*0.89*
30	29.18^{b+}	18.23^{b*}	*2.89*	$11.76^{ab\neq}$	$9.88^{a\neq}$	*1.21*
45	31.57^{a+}	19.11^{a*}	*2.32*	$14.53^{a\neq}$	$8.75^{ab\neq}$	*1.74*
60	29.51^{b+}	18.24^{b*}	*2.17*	$13.16^{ab\neq}$	$7.88^{b\neq}$	*2.33*
MSD	*0.42*	*0.09*		*1.91*	*1.61*	

Means with the same letter within a column are not significantly different at $P \leq 0.05$

Running ANOVA of the moisture data, it was observed that an interaction between Location and *Zai* pits (***Table 4.1***) was significant in most of the weeks but not in others. It is also evident that interaction between Manure and *Zai* pits was significant in few weeks of the growing season in both growing sites.

Moisture recorded showed an upwards trend, increasing successively through the growing season in both Katumani sites (***Figure 4.4a***) and Naivasha site (***Figure 4.4b***). Worth noting is the fact that moisture data from Naivasha site was significantly and continuously higher than the data recorded from Katumani site, as depicted in ***Table 4.5***.

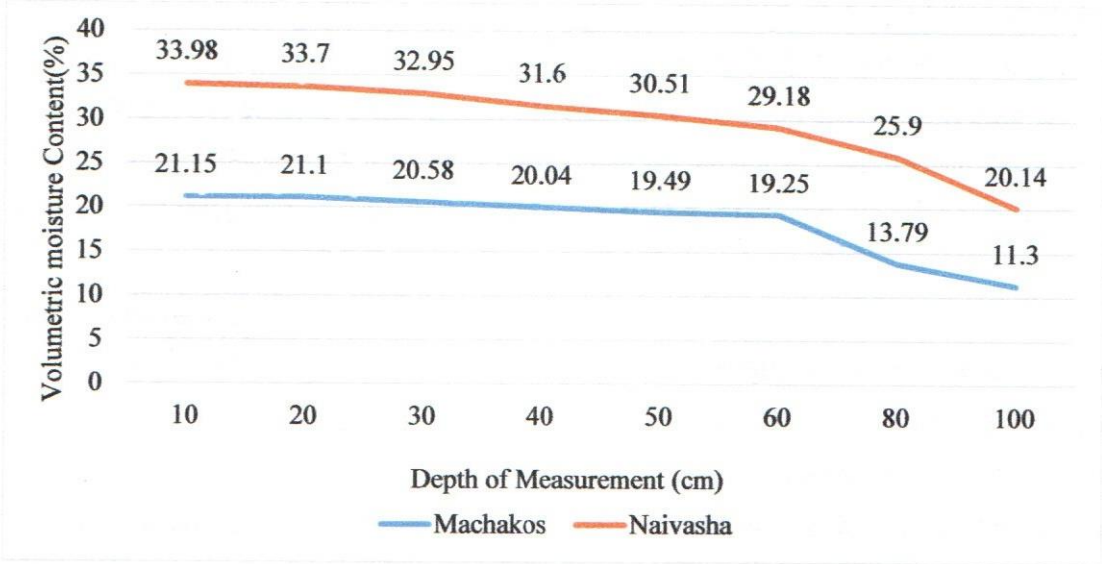


***Figure 4.5**: Variations of Volumetric soil moisture content (%) as influenced by the depth of measurement up to 1 m deep into the soil.*

The reading depth (level of probe measurement) also influenced the volumetric moisture content measured. After installation of access tubes and returning half of the soil back to the pits, the level of the soil in the *Zai* pits represented the soil surface for each pit and from this level, first reading of the moisture was taken at 10 cm downwards. Depth variation helped in determining moisture content at various rooting depths. Moisture content at 10 cm and 20 cm measuring levels were not significantly different while other reading depths i.e., 30 cm, 40 cm, 50 cm, 60 cm, 80 cm and 100 cm were significantly different at $P \leq 0.05$, with 100 cm providing the lowest mean. This trend was observed in both the two locations (***Figure 4.5***).

4.3.2 Influence of *Zai* Pit Technology and Manure Application on Water Use Efficiency

Application of manure also affected WUE (***Table 4.2***), since manure was significant at $P \leq 0.05$, meaning that plots with manure application produced higher WUE compared to plots without manure application.

Zai pits greatly influenced water use efficiency of cowpea. The lowest mean moisture content was observed in flat plots (Z_0) compared to other plots with varying *Zai* pit sizes (***Table 4.1***). Mean separation indicated a significant difference in WUE means from various *Zai* pit sizes, where Z_{45} resulted in higher means (***Table 4.2***). Combining *Zai* pit technology and manure application significantly increased the WUE of cowpea. In ***Table 4.2***) for instance, combining Z_{45} with manure application almost doubled the WUE at 14.53 ($KgHa^{-1}mm^{-1}$)

compared to the WUE from Z_{45} without manure application of 8.75 ($KgHa^{-1}mm^{-1}$). This reinforces the importance of combining the two parameters for better performance.

Water use efficiency was greatly affected by the location difference (***Table 4.1***), since location was significant at $P \leq 0.01$, with Katumani having higher overall mean WUE of 13.06 $KgHa^{-1}mm^{-1}$ while in Naivasha it was on average 9.43 $KgHa^{-1}mm^{-1}$.

4.4 Discussion

Zai pit technology, as demonstrated by the above results, allows for better nutrient and water supply to the crops. Generally, comparing flat plots with plots which had *Zai* pits in terms of soil moisture, significant difference was observed. *Zai* pits increased soil moisture levels by 375% in Naivasha and 418% in Katumani site cumulatively, at the end of data collection period. This makes it better for moisture conservation in the dry areas. This finding is similar to the findings of Kathuli and Itabari (2013) who stated that *Zai* pit technology, can double or even triple soil moisture content. Same findings of tripling of soil moisture content after application of Zai Pit technology were also confirmed by Kimaru - Muchai *et al.* (2020). Z_{45} performed better than the rest of *Zai* pit sizes since it was neither too deep to prompt water logging, nor too shallow to allow drainage and hence loss of the collected water before utilization by plants.

The difference in moisture content in the two locations was brought about by (1) difference in rainfall amounts received in the two locations (Suriya *et al.*, 2015). Naivasha site received a higher rainfall amount of 539.75mm against Katumani site which received 229.81mm hence the higher soil moisture recorded throughout the growth period. The second reason (2) is the fact that Naivasha site has loamy soil (from Particle Size Analysis) which relatively stores water for longer periods (Madhu *et al.*, 2014) compared to Katumani site which has Loamy – Sand soils, which loses the collected water rapidly due to higher infiltration rates of 25.39 mm/hr compared to Naivasha site whose infiltration rate is 18.37 mm/hr.

Time factor had an effect on soil moisture recorded. This is true due to rainfall occurrence continuously throughout the growing season, as well as the ability of *Zai* pits to store water. This means that at any given rainfall occurrence, rain water would increase on top of the previous rainfall, hence the upwards trends (*the cumulative effect*) in soil moisture recorded in both sites. Naivasha received higher average weekly rainfall, coupled with better soil water retention capability (loam soil) hence the higher moisture level throughout the growing period.

The organic nature of manure helps in soil aggregation, which can take place after several days to years. Once the soil particles are aggregated, Aiosa *et al.* (2020) states that specific surface area of the particles increases as well as the number of the pore spaces, but the pore sizes reduce. This minimizes the infiltration rates, as the speed of water passage is reduced, thereby increasing the water holding capacity of the soil. This explains the significant difference of the moisture content of the plots where manure was applied from plots where there was totally no manure application. Better, combining *Zai* pits with manure yields better results on moisture content of the soil. As the pits helps in accumulation of the water, manure helps in retaining the provided water for maximum utilization by plants. These findings are in line with what Kathuli and Itabari (2013) in Makueni county, who stated that combining *zai* pits with manure can increase the final yield up to 4 – 10 times compared to flat plots yields. These findings were also backed up by Kimaru – Muchai *et al.* (2020) in Tharaka – Nithi county, Kenya, where they realized up to 100 – 300% of yield from application of manure in *zai* pitted farms.

There were variations observed in respect to the level of measurement (Reading Depth) of the moisture. There was a continuous reduction in the moisture content measured with increase in depth. This can be attributed to the time factor, that infiltration takes time, hence at the time of measurement, water had not infiltrated into lower levels of measurement. Secondly, it can also be explained by the fact that soil is a heterogeneous entity, meaning that at any given point, none of its elements can be equal, hence the variation in moisture content. It was also observed that the reading depths 60 cm, 80 cm and 100 cm gave the least mean squares during the separation (***Figure 4.5***). This can be attributed to the fact that the *Zai* pits were in a position to collect most of the rainwater and store it for utilization by plants, hence very minimal amounts were able to percolate beyond 70 cm depth. Possibly, beyond this point exists hard rocks, which were observed during PVC tubes installation, hence these rocks could have barred water from percolation and what was quantified in terms of moisture content was water that may have percolated previously before the experimental set – up. Another reason for least water percolation downwards could be due to water loss (collected from the *Zai* pits) through the atmosphere i.e., evapotranspiration, which depends on environmental and climate conditions. This prompted evaluation of water use efficiency, which factors in the dry matter output from a farm and the evapotranspiration from the soil.

Variation in water use efficiency is attributed to many parameters, since it's a derivative of various factors. It is computed as the quotient of total dry weight of a predetermined plot size and crop evapotranspiration (Oluwaseun, 2018). Total dry weight is a factor of treatment

accorded to the soil to guarantee better development that boosts growth parameters and high final yield. Use of *Zai* pits in this experiment facilitated timely supply of crop nutrients in required forms for uptake. This explains why plots treated with *Zai* pits had higher total dry weight at harvest compared to the flat plots. Similar results were observed by Serah (2017) in Tharaka – Nithi, where farmers could get large amounts of biomass at the end of the growing season and these could help in forming animal feeds. Evapotranspiration gains momentum in areas with high exposure to sun's radiations in terms of duration and intensity. Most affected regions according to Hanson *et al.* (1991) are the ASAL regions with low and continuously diminishing vegetation. High ET reduces the WUE of a crop grown, but this is dependent on the performance of the crop in terms of total dry weight (Farias, 2017), as this form the numerator of the derivation, as shown in methodology. This explains the reason for higher means of water use efficiency in Katumani despite having higher sunshine duration and lower rainfall (Farias *et al.*, 2017). Various factors led to the significant difference $P \leq 0.05$ in WUE of the two locations, among them temperature, which when high, prolongs duration of opening of the stomata hence higher transpiration (more water is lost). Higher relative humidity decelerates transpiration rate while high wind speed increases transpiration rate (Mangale *et al.*, 2016).

Tentatively, soil moisture availability and content influences WUE in that less soil moisture results in falling of leaves at early stages, hence low transpiration, that result in moderate WUE (Oluwaseun, 2018). This is what might have resulted in higher WUE in Katumani (12.94 $KgHa^{-1}mm^{-1}$) compared to the lower means in Naivasha (9.46 $KgHa^{-1}mm^{-1}$).

4.5 Conclusion

The study sort to determine the effect of varying *Zai* pits depths and manure levels on soil moisture dynamics and water use efficiency, where the performance of *Zai* pits were highly significant. Time of measurement in terms of weeks also demonstrated a continuously inclining moisture content with respect to time. Manure application was also a factor of consideration and plots with manure application gave remarkably higher results in terms of both soil moisture and WUE. There was a variation of moisture content as the depth of measurement increased underground. At the end of the experiment, there was great difference in Water use efficiency of various *Zai* pit treatments as well as manure treatments. Combining *Zai* pits technology and manure application gave significant results in terms of soil moisture content as well as water use efficiency. This is a clear indication that can boost final yields for farmers in ASAL areas, as reflected by WUE, of which the produced yield is a factor.

4.6 Recommendation

From the study, it is recommended that *Zai* pits be used in areas where there are lower rainfall duration and intensity, since the little amount of rain water can be collected and be stored upto 15 weeks. Depending on the location, the pits should neither be shallow nor too deep for maximum performance. Combining the technology with manure application boosts soil moisture and realizes higher Water use efficiency. We recommend *Zai* pits with 45 cm depth in combination to *recommended* manure application (according to specific soil fertility status) for better soil moisture content, improved water use efficiency and maximum yields in ASAL localities.

CHAPTER FIVE

ASSESSMENT OF GROSS MARGIN OF USING *ZAI* PIT TECHNOLOGY FOR SOIL MOISTURE CONSERVATION IN COWPEA PRODUCTION

Abstract

Gross margin (GM) of a project gives a clear picture of economic viability of a project or business. It determines the profitability at the end of the project or at the end of a financial year for businesses to put strategies in place to maximize on their operations. Cowpeas (*Vigna unguiculata* L. Walp) is an important crop in the dry regions of Kenya; therefore, improvement of its production is essential. To boost its production, *Zai* pit technology was used in two dryland sub-counties i.e., Naivasha and Katumani with the main aim of comparing the Gross margin of farms where the technology was used, to farms where it was not applied. The *Zai* pits were of three depths, 30 cm, 45 cm and 60 cm, and their performance were compared with flat (0 cm) plots. Manure was applied to some plots while there was no manure application in other plots, such that the field was laid out in Split Plot arrangement with manure levels (Manure and No Manure) as the main plot factors while *Zai* pit sizes as sub – plot factors. GM was then calculated by getting the difference between Total revenue and Total variable cost. It was asserted that the GM for *Zai* pitted farms were higher (33.49%) compare to flat farms (2.04%). A 45 cm *Zai* depth in Naivasha produced the largest gross margin of KES 57,166.22 (521.35 USD) while Flat plots produced the least KES. 9,245.45 (84.32 USD). Compared to other depths, Flat plots (0 cm *Zai* depth) in Katumani gave a negative GM of KES. -3,067.39 (i.e., let to a loss of 27.97 USD), proving the great effect of *Zai* pit technology in improving the farm revenue. This study proved significance ($P \leq 0.05$) and profitability of using *Zai* pit technology in production of Cowpeas in ASAL regions of Kenya.

Keywords: Gross Margin, *Zai*, Pits, Manure, Machakos, Naivasha, Total Revenue, Total Variable cost

5.1 Introduction

With the ever-increasing world population with agricultural production in the downward trend due to shrinking arable land, future generation is likely to suffer from food insecurity (Ahn & Norwood, 2020) more so, the communities based on the ASAL regions of the Sub – Saharan Africa (SSA). Agriculture in these localities has proven to be a challenge due to low soil moisture, which is one of the results of climate change. Low soil moisture leads to poor crop performance from these regions, that greatly affect the yields from the farm. Meagre farm yields lead to increasing demand for nutritious foods to sustain livelihood in these

areas ASAL (Korir *et al.*, 2020). Therefore, there is a necessity for improvement in agricultural practices by employing any interventions necessary to boost the yields from the farms. Such interventions should be in a position to address the key limitations of agriculture in these regions, the main one being water scarcity (Koech *et al.*, 2020). Not all farmers can afford irrigation in their farms, hence they depend on rainfed agriculture, but the rains in the ASALs are unreliable and scarce (Rabach *et al.*, 2020), so when they come, farmers need to make good use of it. One intervention that can make better use of the erratic rains in the ASAL regions is *Zai* pit technology.

Use of *Zai* pits is a technology that helps in collecting the (erratic and unreliable) rain water and concentrating it within the sub – soil, where the plant roots can access and use it (Kimaru – Muchai *et al.*, 2020) for utilization. This promotes growth and development of crops in the arid soils, thereby guaranteeing good harvest at the end of the season.

It is the goal of every farmer to maximize output from his/her farm, whether for subsistence or commercial purposes. This is a motivation as it guarantees a return on investment for commercial farmers and this ensures continued and sustainable production (Jirgi *et al.*, 2020.). *Zai* pit technology aims to boost the soil moisture content in the ASAL soils, hence farmers are in a position to obtain higher yields that guarantee good return once sold, putting them in better position to meet their cost of production cost and in addition, gain a profit from their venture (Onuk *et al.*, 2020).

For farmer to actuate good returns, it all depend on the commodity/crop being produced, availability of its market and the market prices, putting into the account the price fluctuations (Lomeling & Huria, 2020). Therefore, Cowpeas (*Vigna unguiculata*) farmers should be better planners and only produce after conducting the market research () and plan to harvest when the demand is high (Segun-Olasanmi & Bamire, 2010). This guarantees market for the produce.

The productivity of cowpea can be increased by the use of scientific technologies like *Zai* pits which helps in a firming food security (Kimaru – Muchai *et al.*, 2020). Poor farm produce are consequences of lack of fertilizers at the right time (including the technical know-how of the right fertilizer source to use, right amounts, right time of application and the right placement point) (da Silva *et al.*, 2020), shortage of labour, lack of technical knowledge on pest management and topographical barriers (Ahmed *et al.*, 2020). On top of these, poor markets limit farmers' income, hence poor returns that reduce the farmers' morale. This research would help the policy makers and researchers in identification of potential area for intervention as well. (Sanjiv – Subedi *et al.*, 2019)

Plant varieties differ from each other in terms of production cost, gross return and gross margin (Sogoba *et al.*, 2008). Due to soil treatments, environmental conditions and cultivation practices, production of cowpeas significantly vary from one location to the other, as well as from one *Zai* pit depth size to the other in the ASAL areas of Kenya (Kimaru – Muchai *et al.*, 2020). Currently, a few studies are available in production cost, gross return and profitability analysis of Cowpeas in Kenya. There is a need to analyse the economic aspect of Cowpeas production in dryland agriculture to enhance farm production.

Zai pit technology makes use of relatively sized planting holes to trap water, which is then used in growth and development of crops. These holes are customized based on location of use, since the pits respond to various agroecological zones differently. Comparing the performance of these pits with farms where the technology was not applied gives interesting results economically, proving that the technology is profitable (Mwangi, 2020). Profitability of any venture/agricultural project can be measured using various techniques, one of them being the use of Gross margin (GM) (Onuk *et al.*, 2020), which takes care of all costs and all revenues. The present study aims to analyse the gross margin of cowpeas grown under varying *Zai* pit depths in the ASAL localities of Kenya.

5.2 Materials and Methods

The experiment was carried out in Naivasha within Nakuru county and Katumani within Machakos county. This study involved use of the stated two study sites, on which the experiment was laid out in a split plot arrangement, with two manure levels (manure and No manure) as main plot factors and Four *Zai* pit depth (cm – Flat farms, 30 cm, 45 cm and 60 cm) sizes as the sub – plot factors. Cowpeas – M66 variety was used, which was planted and after thinning, gave a plant population of 120 plants per sub – plot.

After harvest, the gross margin (GM) was calculated using the cowpeas market prices of the two counties (Nakuru and Machakos). This was to facilitate the nearness of market to farmers in order to eliminate unnecessary transport cost.

GM is mathematically derived from costs and revenues of a project, such that GM is the difference between total revenue and total variable cost (*equation 5.1*) (Segun-Olasanmi & Bamire, 2010);

$$GM = Total\ Revenue\ (TR) - Total\ Variable\ Cost\ (TVC) \quad \text{..... equation 5.1}$$

while:

$$TR = Quantity\ (Q) \times Current\ Market\ Price(P) \quad \text{..... equation 5.2}$$

Where;

GM is the Gross margin, TR is the Total revenue, TVC is the total variable cost, Q is the quantity/unit of measurement of the commodity and *P is the current market price of a unit of measurement.*

The Total Variable Cost included the costs incurred during Land preparation, acquisition of manure and seeds, planting cost, weeding cost as well as harvesting cost. Larger proportion of the variable cost was constituted of the labour incurred in terms of land preparation, manure application, weeding and harvesting and was incurred at 500 per man-days. After computations, the GM realized for each treatment were analysed using split plot design in SAS version 9.2, where analysis of variance was carried out, followed by mean separation using Tukey's honestly significant difference at 5%.

5.3 Results

Analysis of Variance reveals a significant difference in the yields from the two locations (Katumani and Naivasha). To work out the total revenue, the yields obtained per hectare were multiplied by the local price (*equation 5.2*) of the cowpeas per kilogram. As at November 2020, the local price in Katumani was KES 170.00 while the price in Naivasha was KES 155.00. Same prices were documented by Sokoplus (2020). The total variable cost was worked out as per ***Table 1***, showing expenditure of each item per site.

Table 5.1: Total variable cost (January – December 2020) derived from expenditure of each production factor as per the study site

Item	Variable Cost Per Ha (KES)	
	Katumani	Naivasha
Land preparation (Labour)	56,973.39	44,510.38
FYM (Cow)	10,000.00	5,000.00
Seeds	400.00	400.00
Planting (Labour)	4,945.59	4,945.59
Weeding (Labour)	19,782.39	19,782.39
Harvesting (Labour)	9,891.19	9,891.19
Total Variable Cost (KES)	**101,992.56**	**84,529.55**

Yield being a factor in gross margin computation, leads to an influence in the performance of the cowpeas in terms of gross margin and it was significant at $\alpha = 0.05$, with

Naivasha (**Table 5.2**) giving constantly largest gross margin after doing mean separation across all *Zai* depths.

Table 5.2: Gross Margin (KES/Ha) of Cowpea as influenced by *Zai* depth (cm) per Location

Zai depth (cm)	Gross Margin (KES/Ha)		
	Katumani	**Naivasha**	***MSD***
0	-3067.39^{c*}	9245.45^{c+}	***7432.89***
30	48173.96^{a*}	49803.72^{b+}	***1254.86***
45	54354.91^{b*}	57166.22^{a+}	***9757.23***
60	48740.91^{a*}	50574.72^{a+}	***6904.54***
MSD	***5653.86***	***3975.53***	

Means with the same letters (within a column) or same symbols (across rows) are not significantly different at $P \leq 0.05$

Zai pits depth, being under investigation in this study revealed a great significance ($P \leq 0.001$) in gross margin after running ANOVA. Gross margins were significantly higher for *zai* pitted plots as compared to flat plots as represented in ***Table 5.2*** and ***Table 5.3***.

Table 5.3: Cowpea performance in terms of Gross Margin (KES/Ha) as influenced by combination of Manure and varying *Zai* depths (cm)

Zai depth (cm)	Gross Margin (KES/Ha)		
	With manure	**Without Manure**	***MSD***
0	2288.90^{d*}	3889.15^{c+}	***982.45***
30	46563.94^{c*}	45930.48^{b+}	***3335.16***
45	56426.65^{a*}	51413.73^{a+}	***4533.71***
60	51476.65^{b*}	49092.98^{ab+}	***4522.85***
MSD	***3578.78***	***4913.94***	

Means with the same letters (within a column) or same symbols (across rows) are not significantly different at $P \leq 0.05$

Mean separation using Tukey (at $\alpha \leq 0.05$) provided evidence of higher gross margin from *Zai* pits of 45 cm with a mean percentage of 35.36% while flat plots tailing with a mean percentage of 1.96% (***Figure 5.1***). This shows the significant performance of *Zai* pit technology in cowpeas production as compared to flat farms.

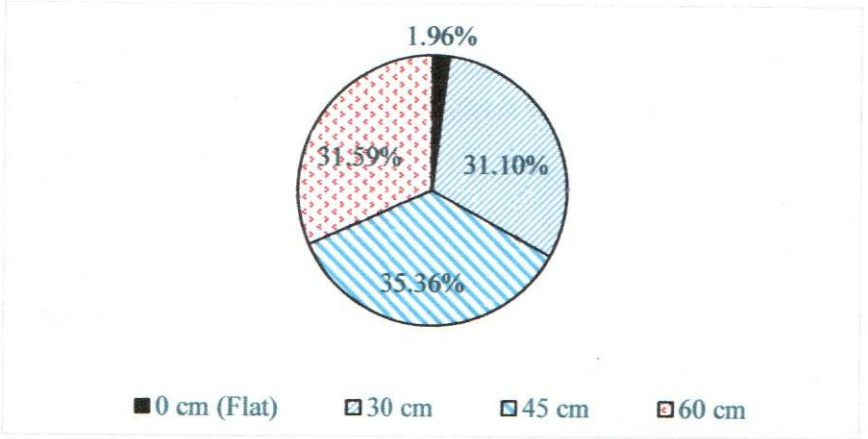


***Figure 5.1**: Percentage Gross Margin performance of Cowpeas as influenced by Zai Depths (Combined for both sites since the trend was similar).*

5.4 Discussion

Gross margin is an accounting element derived from the returns from the farms and the variable costs incurred during the production process. It is a means to measure the profitability of a venture/farm production (Onuk *et al.*, 2020). In agriculture, GM it is directly proportional to the yield (Jirgi *et al.*, 2020), therefore this is the reason for farmers to strive to get higher yield in order to maximize the profits in terms of gross margin. Therefore, the farms where yields were higher, a larger gross margin was realized. On the other hand, gross margin is inversely proportional to the variable costs (Lameling & Huria, 2020), hence a farmer should strive to reduce the expenditure on these factors in order to maximize profits. From derivation of TVC, it is evident that labour constituted the highest cost of production, at 89.8% in Katumani and 93.6% in Naivasha. This explains the high variable costs that significantly reduced the gross margin.

The significance of the GM from the two locations revealed differences in yield performance. Although Katumani fetched high returns from the produce, Naivasha site had low (production) total variable cost (TVC) hence this explains higher GM computed in Naivasha.

Zai pit technology was a major player in this study, as its effects were evident in all aspects. Comparison of gross margin from *Zai* pitted farms with GM from flat farms, which revealed a significance ($P \leq 0.05$) can be explained by the fact that the technology helps in harvesting the rain water and delivering it to the plants in the required periods hence the plants are able to utilize this water to achieve higher yields (Fredlund & Houston, 2013). This was also a deduction by Kimaru – Muchai *et al.* (2020) who documented the ability of *Zai* pits to collect and store rainwater that boosted the yields from farmers' fields in the dry North –

Eastern parts of Kenya. The higher yields then contribute to the high GM obtained from *Zai* pitted farms. This also explains the lower percentage in GM of 1.96% from the flat farms (i.e., farms with 0 cm *Zai* depth), indicating that low yields were realized from flat farms that in turn reduced the gross margin.

5.5 Conclusion

This study reveals what a great investment the *Zai* pit technology is in comparison with the flat farm cultivation. Although it needs intensive labour, the returns, as indicated by the gross margin is lump sum and beneficial economically. Labour cost takes largest portion of the total variable cost since implementation of *Zai* pit technology is labour intensive, but this is compensated by the high yields that are obtained from the technology. Therefore, given these circumstances, the farmer is still in a position to realize good profits, as reflected by the large gross margins.

5.6 Recommendation

Results from this study indicates that productivity could be improved if the farmers were to adopt the technology. Although *Zai* pitted plots performed better than flat plots, this study was for a short period of time. A longer period of time with repeated seasons is hereby recommended to ascertain and affirm the findings of higher GM in *Zai* pitted farms.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 Discussion

All the parameters observed in the experiment were impacted significantly by the *Zai* pits technology, which was a planting technique aimed at precise application of soil amendments (Sawadogo, 2011). *Zai* pits influence on soil parameters such as inorganic nitrogen, extractable phosphorus and soil volumetric moisture content is a clear indication of its effectiveness in improvement of nutrient availability as well as soil water conservation from maximum crop production. Kimaru – Muchai *et al.* (2021) states that *Zai* pits harvests water and concentrates it for utilization by crops. At the same time, the collected water can be used in the dissolution of nutrients from the unavailable forms e.g. ammonium ions to available forms like Nitrates that plants can readily access for utilization in their system. This makes nutrients concentrations in the soils increase their availability. Inorganic nitrogen and extractable phosphorus are proportions of Total nitrogen and total phosphorus (respectively) that are actually available and can be up – taken by the plants (Roswall *et al.*, 2021). From the results, these increased significantly.

Significance of results in different *Zai* depths indicated that the size of the Zai pits matter in the achievement of the targeted outcomes. Too shallow pits should be avoided as they may not achieve any desired outcome while too deep pits should also be avoided (Alemayehu *et al.*, 2021). From the experiment, *Zai* pits with 45 cm depth produced desirable results in terms of nutrient improvement. This can be associated by the amount of water that may have been collected in the pits, which was neither too much nor too low hence played a better role in the dissolution of the nutrients and improve their availability (Silva *et al.*, 2020).

Amount of soil moisture measured from the different *Zai* pit sizes differed significantly due to the fact that flat plots (0 cm deep) doesn't collect water, therefore, once the soil has absorbed enough water in case of an occurrence of rainfall, the excess water drains away i.e. the soil only holds gravitational water, which drains away after 24 hours leaving behind capillary water. Shallow *Zai* pits like 30 cm hold some water, but not enough. This water drains away (gravitational water) and the remaining capillary water easily percolates deep to the underground levels since Aridisols have large pore spaces that cannot hold water for long. This water gets lost within short periods like within 24 – 48 hours, leaving plants with less moisture for survival. Too deep *Zai* pits like the 60 cm are not desirable. This is because they collect too

much water that affect the crops growth and survival. In the experiment, they greatly affected cowpeas productions in the Oxisols of Naivasha site, since they led to water logging and cowpea, could barely survive in such. This therefore greatly affected the yields from the Oxisols. 45 cm *Zai* depth collected neither too low nor too much water, hence crops optimally used this and were generally healthier.

Significant impacts of *Zai* pits were also observed in the plant height and stem diameter, which are physical characteristics of plants which are adequately supplied with enough nutrients and water are in a position to grow well under no stress and will be healthy thought their lifespan. This is because everything needed is available at correct time. Therefore, a well-fed crop will have good height and a wide – enough stem girth. Similar scenario, *Zai* pits supply water and nutrients precisely to the plant roots hence crops utilize when needed to grow well and healthily.

Organic amendments are the safest soil conditioners that play great roles in the soil. They have relatively few to none negative effects top soils as their merits outweigh their negative impacts (Dadrasnia *et al.*, 2021). Manure application has the ability to improve soil physical as well as biological conditions. It is also in a position to supply various plant nutrients for crop production. These include both macro- and micro- essential plant nutrients (Gross & Glaser, 2021), hence it's an all – round amendment for soils.

Among the essential macronutrients supplied by the FYM are the nitrogen and phosphorus. These are most important nutrients and are required by plants in large amounts (Dotaniya *et al.*, 2021). During decomposition process of manure, protein, uric acid, and urea are broken down into ammonia and ammonium ions which are later converted into nitrates, a form of nitrogen that is directly utilized by the crops for growth and development (Christou *et al.*, 2021).

6.2 Conclusions

Investing in better innovations like *Zai* pit technology is key as it is an intervention proven by this research to improve selected soil chemical properties like soil inorganic nitrogen and extractible phosphorus. Since these are macronutrients, their presence in sufficient amounts in the soil and in available form triggers uptake hence growth parameters like cowpea height and stem diameter are favoured significant. Favourable conditions created by the technology

helps in availing the residual plant nutrients for uptake. These, plus the nutrients from the added manure are utilized by plants to improve plant performance. Significance was observed in the cowpea plant tissue analysis, noting that total nitrogen (N_T) and total phosphorus (P_T) were higher in plots with added manure as well as in plots that were treated with *Zai* pits. Combining both pits and manure significantly increased these parameters and the final yields of cowpea were significant, an indication of the importance of the combination. This proved the importance of this research.

Soil moisture dynamics and cowpea water use efficiency were also under investigation. Soil moisture content was tracked right from the beginning of the season (weekly) to the harvest time, using Soil Neutron Probe (Model: TROXLER 4300 DMG) (Johnson *et al.*, 2013) where each subplot had an access tube, up to 100 cm deep. Comparing moisture from various *Zai* pit depths to moisture from flat farms and the difference were significant. Higher soil moisture levels were recorded in *Zai* pits with depths of 45 cm and 60 cm. The 30 cm depths were lower but flat plots with no *Zai* pits had the least (below the overall average). Time of measurement (weeks) was also significant. There was an upward trend in soil moisture recorded through time. Soil moisture reduced tremendously with increase in depth of measurement. The values measured at 100 cm deep were almost constant throughout all the period and across all treatments.

Water use efficiency was evaluated after harvest and there was significant difference among the *Zai* depth treatments. WUE was greatly affected by manure application. Given that yield is a factor of water use efficiency, once the yield has been improved by manure, automatically, WUE was improved.

The economic viability of this technology was also assessed through the use of gross margin (GM), which is the difference between the total revenue and the total variable cost. Larger GM means great performance and good viability. Significance was observed across the treatments and *Zai* pits with 45 cm depth proved profitable (Significant at $P \leq 0.005$), since it had lower costs and good returns, giving the largest GM across the two locations. By using this technology, food insecurity in the ASAL rural areas of Kenya, which are occupied mainly by smallholder farmers, will be eradicated.

6.3 Recommendations

From the findings and conclusions, the following recommendations can be made:

i. This research and the data generated are beneficial to (i) farmers in the ASAL areas who strive to improve yields from their farms, (ii) extension officers who are mandated

to advising farmers on agricultural technologies and (iii) researchers who wish to extend their research on *Zai* pit technology, since this work has been published, hence documentation is available.

ii. *Zai* pits should be tested in each of the ASAL regions to ascertain the best *Zai* depth for the regions. This will cater for the varying soil types which have varying water holding capacities, different fertility status that later influences the potential grain yield.

iii. The amount of manure to be added to each of the soils and different average rainfall amounts, hence avoid water logging, as was observed in some 60 cm pits in Naivasha field. This is key since manure may not be available in plenty and therefore quantifying the specific amount to be used in a specific depth of Zai pit is very important.

iv. Too deep *Zai* pits or too shallow ones should be avoided. The shallow ones do not store enough water for the plants while too deep ones can lead to water logging, or can hold water too deep, beyond some plants' rooting depth, unless the plant being produced is deep rooted. These, evidently, depend on locations which have heterogeneous soil properties; therefore, this research should be done in various sites to come up with specific Zai depth for each site.

v. To save on cost, 45 cm *Zai* depth should be used for maximum returns, since it gave the largest gross margin. But this should be done over repeated seasons to ascertain consistency.

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APPENDICES

Appendix I: Areas for Further Study

i. Since this study was only carried out in two counties of Kenya, other counties with ASAL characteristics should also be investigated.

ii. The study can be done in rainout shelter, glass house nor greenhouse to account for the varying rainfall amounts in different locations.

iii. This study should be carried out repeatedly for various planting seasons for maximum impact on the desired soil characteristics which will lead to affirmation of the results.

Appendix II: Anova Tables for Chapter Three

(a) Analysis of Variance for Soil Inorganic Nitrogen (N_{in})

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	6.07	6.07***	139.75	<.0001
Replication	3	0.04	0.01	0.38	0.7654
Manure	1	13.42	13.42***	309.03	<.0001
Location×Manure	1	0.05	0.05	1.15	0.2891
Error A	3	0.02	0.01		
Zai Depth	3	0.64	0.21**	4.98	0.0048
Location× *Zai* Depth	3	0.04	0.01	0.31	0.8181
Manure× *Zai* Depth	3	0.48	0.16*	3.69	0.0190
Location×Manure×*Zai*Depth	3	0.20	0.06	1.54	0.2188
Error B	42	1.82	0.04		
Total	63	22.81			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(b) Analysis of Variance for Soil Extractable Phosphorus (P_{ex})

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	1766972.02	1766972.02***	2727.83	<.0001
Replication	3	1126.66	375.55	0.58	0.6315
Manure	1	37171.84	37171.84***	57.39	<.0001
Location×Manure	1	22485.00	22485.00***	34.71	<.0001
Error A	3	2600.56	866.85		
*Zai*Depth	3	4348.51	1449.50	2.24	0.0979
Location×*Zai*Depth	3	4108.91	1369.63	2.11	0.1128
Manure×*Zai*Depth	3	1352.41	450.80	0.70	0.5597
Location×Manure×*Zai*-Depth	3	1031.32	343.77	0.53	0.6637
Error B	42	27205.83	647.76		
Total	63	1868403.09			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(c) Analysis of Variance for Plant Total Nitrogen (N_T)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	0.68	0.68***	37.26	<.0001
Replication	3	0.03	0.01	0.67	0.5758
Manure	1	1.70	1.70***	92.57	<.0001
Location×Manure	1	0.19	0.19**	10.44	0.0024
Error A	3	0.06	0.02		
*Zai*Depth	3	0.06	0.02	1.21	0.3191
Location×*Zai*Depth	3	0.07	0.02	1.32	0.2800
Manure×*Zai*Depth	3	0.09	0.03	1.69	0.1836
Location×Manure×*Zai*Depth	3	0.02	0.01	0.40	0.7512
Error B	42	0.77	0.02		
Total	63	3.71			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(d) Analysis of Variance for Plant Total Phosphorus (P_T)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	0.021	0.021***	58.250	<.0001
Replication	3	0.002	0.001	2.060	0.1203
Manure	1	0.004	0.004**	12.200	0.0011
Location×Manure	1	0.000	0.001	1.360	0.2509
Error A	3	0.002	0.001		
*Zai*Depth	3	0.001	0.001	1.130	0.3470
Location×*Zai*Depth	3	0.004	0.001*	3.850	0.0159
Manure×*Zai*Depth	3	0.000	0.001	0.600	0.6206
Location×Manure×*Zai*Depth	3	0.002	0.001	2.340	0.0874
Error B	42	0.016	0.004		
Total	63	0.056			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(e) Analysis of Variance for Plant Diameter (cm)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	0.05	0.05***	15.66	0.0001
Replication	3	0.04	0.01	4.17	0.0069
Manure	1	0.04	0.04***	13.57	0.0003
Location×Manure	1	0.01	0.01	1.05	0.3071
Error a	3	0.02	0.01		
*Zai*Depth	3	0.07	0.02***	7.22	0.0001
Location×*Zai*Depth	3	0.01	0.01	0.75	0.5215
Manure×*Zai*Depth	3	0.01	0.01	1.72	0.1636
Time	3	0.80	0.26***	79.47	<.0001
Location×Time	3	0.02	0.01	2.27	0.0817
Manure×Time	3	0.01	0.01	0.58	0.6264
*Zai*Depth×Time	9	0.01	0.01	0.37	0.9491
Location×Manure×*Zai*De×Time	33	0.05	0.01	0.50	0.9892
Error b	186	0.63	0.01		
Total	255	1.81			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(f) Analysis of Variance for Plant Height (cm)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	3472.15	3472.15***	282.32	<.0001
Replication	3	82.26	27.42	2.23	0.0862
Manure	1	75.47	75.47*	6.14	0.0141
Location×Manure	1	4.46	4.46	0.36	0.5477
Error a	3	394.12	131.37		
ZaiDepth	3	30.01	10.00	0.81	0.4879
Location×ZaiDepth	3	8.68	2.89	0.24	0.8716
Manure×ZaiDepth	3	146.12	48.70*	3.96	0.0091
Time	3	58217.71	19405.90***	1577.87	<.0001
Location×Time	3	9749.73	3249.91***	264.25	<.0001
Manure×Time	3	85.01	28.33	2.30	0.0784
ZaiDepth×Time	9	42.47	4.71	0.38	0.9419
Location×Manure×ZaiDepth ×Time	33	324.01	9.81	0.80	0.7752
Error b	186	2287.58	12.29		
Total	255	74919.84			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

Appendix III: Anova Tables for Chapter Four

(a) Analysis of Variance for Soil Moisture (%)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	266420.91	266420.91***	44029.8	<.0001
Replication	3	74.00	24.66	4.08	0.0067
Manure	1	696.07	696.07***	115.04	<.0001
Location×Manure	1	23.34	23.34*	3.86	0.0496
Error a	3	43.43	14.47		
ZaiDepth	3	5032.06	1677.35***	277.21	<.0001
Location×ZaiDepth	3	808.04	269.34***	44.51	<.0001
Manure×ZaiDepth	3	36.89	12.29	2.03	0.1070
Time	15	386761.19	25784.07***	4261.18	<.0001
Location×Time	15	15601.92	1040.12***	171.90	<.0001
Manure×Time	15	779.35	51.95***	8.59	<.0001
ZaiDepth×Time	45	4195.07	93.22***	15.41	<.0001
ReadingDepth	7	124961.11	17851.58***	2950.22	<.0001
Location× ReadingDepth	7	3533.12	504.73***	83.41	<.0001
Manure× ReadingDepth	7	144.00	20.57***	3.40	0.0012
ZaiDepth× ReadingDepth	21	1728.70	82.31***	13.60	<.0001
Time× ReadingDepth	105	31221.72	297.34***	49.14	<.0001
Error b	7936	48021.16	6.05		
Total	8191	890081.15			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

(b) Analysis of Variance for Water Use Efficiency ($KgHa^{-1}mm^{-1}$)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	127.54	127.54**	7.78	0.0077
Replication	3	150.73	50.24*	3.06	0.0375
Manure	1	161.61	161.61**	9.86	0.0030
Location×Manure	1	9.22	9.22	0.56	0.4570
Error a	3	9.29	3.09		
ZaiDepth	3	136.69	45.56	2.78	0.0519
Location×ZaiDepth	3	108.33	36.11	2.20	0.1009
Manure×ZaiDepth	3	98.34	32.78	2.00	0.1276
Error B	45	737.91	16.39		
Total	63	1539.70			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively.

Appendix IV: Anova Tables for Chapter Five

(a) Analysis of Variance for Gross Margin (KES)

Source	Degree of Freedom	Sum of Squares	Mean Squares	F - Value	Probability
Location	1	1513654173	1513654173*	7.05	0.0109
Replication	3	636223003	212074334	0.99	0.4072
Manure	1	41342248	41342248	0.19	0.6629
Location×Manure	1	44722405	44722405	0.21	0.6503
Error a	3	1033844127	344614709		
ZaiDepth	3	26741686522	8913895507**	41.51	<.0001
Location×ZaiDepth	3	507683855	169227952	0.79	0.5069
Manure×ZaiDepth	3	401153691	133717897	0.62	0.6040
Error B	45	9663378182	214741737		
Total	63	40583688206			

*, **, *** represents significance at 0.05, 0.01 and 0.001 respectively

Appendix V: Pictorials

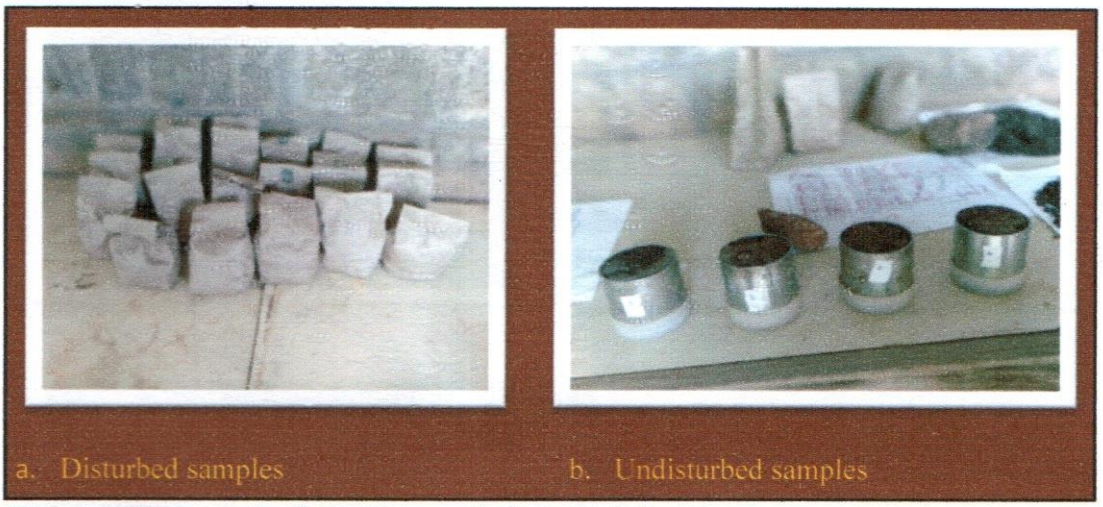


Figure 1: Soil samples for various analysis in the Laboratory

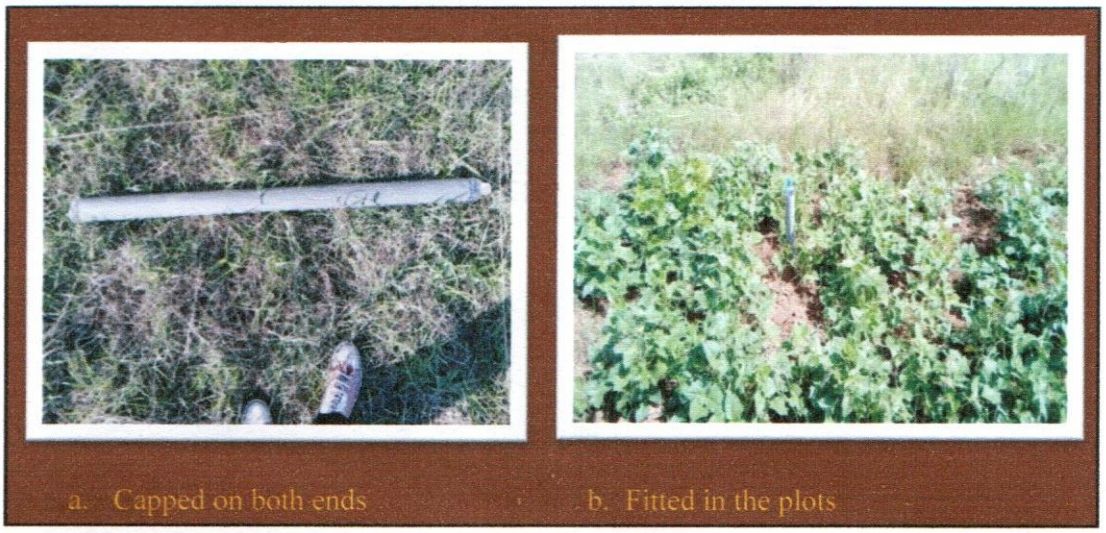


Figure 2: Access tubes *(PVC)*



Figure 4:

Field appearance at 7 weeks after planting

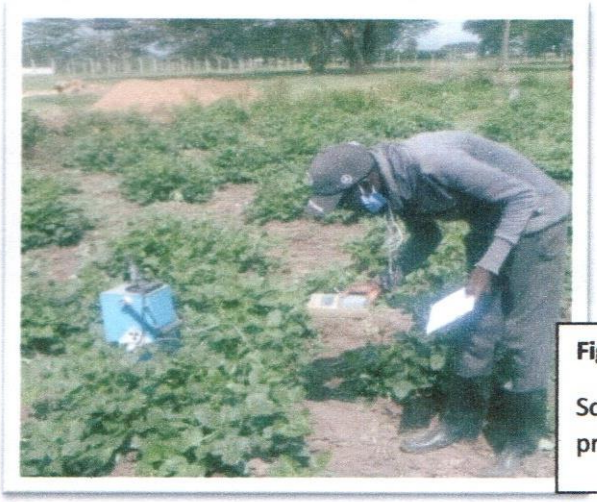


Figure 5:

Soil moisture reading using Neutron probe



Figure 6:

Cowpea pods

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Apendix vii: Publication

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Zai Pit Effects on Selected Soil Properties and Cowpea (*Vigna unguiculata*) Growth and Grain Yield in Two Selected Dryland Regions of Kenya

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Abstract

Erratic rainfall and temperature regimes, strongly affect agricultural productivity. To address the reduction in production, this study assessed the effect of *Zai* pit depths on selected soil properties and cowpea growth and grain yield. *Zai* pit technology was tested in two locations falling under Agroecological Zone IV (relatively dry areas) *i.e.* Machakos in Machakos County and Naivasha in Nakuru County, Kenya, aiming to determine the combined effect of four *Zai* pit depths and two levels of manure (plots with manure and plots without manure) on selected soil properties, growth and yield of cowpea. Experiment was laid out in split plot arrangement, with manure levels as the main plot factor and *Zai* pit depths (Flat: Z_{op}, 30 cm: Z_{tp}, 45 cm: Z_{fc}, and 60 cm: Z_{sp}) as subplot factor, replicated four times. Cowpea (M66 variety) was used as the test crop. Inorganic nitrogen (N_{in}) and extractable phosphorus (P_{ex}) were significantly ($P < 0.05$) higher, at 1.37 mg·kg^{-1} for N_{in} and 80.4 mg·kg^{-1} for P_{ex} in *Zai* pits compared to flat plots which were at 0.91 mg·kg^{-1} for N_{in} and 47.1 mg·kg^{-1} for P_{ex}. The values of N_{in} and P_{ex} also varied depending on depths, with Z_{fc} having highest N_{in} at 1.17 against the least, at 0.89 in the Z_{op}, while Pex was highest in Z_{tp} at 102.3 mg·kg^{-1} while Z_{sp} having the least P_{ex} of 89.7 mg·kg^{-1}. Generally, crops in *Zai* pitted plots were larger in diameter (0.46 cm) and height (34.20 cm) than crops in flat plots at (0.42 cm) and (18.11 cm) diameter and height respectively. Better performance was observed in yield, with Z_{fc} yielding 853.33 kg·Ha^{-1} against 685.0 kg·Ha^{-1} in Flat plots in Machakos while 931.66 kg·Ha^{-1} in Z_{fc} against 563.33 kg·Ha^{-1} from Flat plots in Naivasha. This study demonstrated great potential of *Zai* pit technology on crop production, as reflected on improved growth and yield of cowpeas. Combining *Zai* pits with manure increases soil N_{in}, P_{ex} and is a guarantee of great crop performance in terms of high final yields.

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