

**INTEGRATION OF TIED RIDGES AND FERTILIZER USE TO ENHANCE
WATER AND NITROGEN USE EFFICIENCIES FOR MAIZE PRODUCTION
IN SEMI-ARID LANDS**

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DECLARATION**Declaration by the Candidate**

This thesis is my original work and has never been presented for the award of an academic degree in any other university and should not be copied or reproduced in any format without written authority from the author and/or the University of Eldoret.

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DEDICATION

A journey of a thousand miles starts with a single step. By God's grace, it is finished
VOILA!!!

I dedicate this work to my special and lovely parents Bsp. Silvanus & Mrs. Julia Alwang'a Malaho, who have not only encouraged me but prayed for me and have been strong pillars in my life during this entire period. Also, my mother-in-law, who always prayed for me to finish this work successfully.

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GREAT IS THY FAITHFULNESS, OH LORD!

ABSTRACT

Low maize (*Zea mays* L.) production in arid and semi-arid lands (ASALs) has been attributed to inadequate soil moisture and declining soil fertility. This could be improved through enhanced water use efficiency (WUE) and nutrient use efficiency (NUE). During the short rain (SR) seasons of 2013 and 2014, a study was conducted at Kenya Agricultural and Livestock Research Organization (KALRO) – Katumani Research Station to monitor WUE, NUE and grain yield in maize production. A 2*2*4 factorial trial of cropping seasons, soil moisture conservation (tied versus untied ridging) and fertilizer types (control, CAN, FYM, CAN + FYM) were set up in a Randomized Complete Block Design (RCBD). Rainfall data was put together for the entire study period. Soil and manure analysis were also done. Soil moisture content was monitored using a neutron probe moisture meter, CPN 503-DR. Analysis of variance was executed on soil moisture, maize grain yield and water and Agronomic Nitrogen Use Efficiencies using GENSTAT statistical software 14th edition. Treatments with significant differences were separated using Tukey's at 95% confidence intervals. In both seasons, treatment combinations under untied ridges had higher soil moisture than those in tied ridging. Plots with tied ridges had higher WUE ($1.87\text{kg mm}^{-1}\text{ ha}^{-1}$) compared to those with untied ridges ($1.00\text{kg mm}^{-1}\text{ ha}^{-1}$). Tied ridge plus FYM plots recorded the largest WUE in both SR 2013 ($2.9\text{ kg mm}^{-1}\text{ ha}^{-1}$), SR 2014 ($3.6\text{ kg mm}^{-1}\text{ ha}^{-1}$) and in overall ($3.23\text{kg mm}^{-1}\text{ha}^{-1}$). On average, maize yields were 53% higher in 2013 than in 2014 SR. FYM in tied ridges resulted in larger yields (294kg ha^{-1}) compared to untied ridges (152kg ha^{-1}). Tied ridges ($3.75\text{kg grain}^{-1}\text{ kg N}^{-1}$) had higher NUE than untied ($-0.75\text{kg grain}^{-1}\text{ kg N}^{-1}$). In both SR 2013 (6.6 kg Nha^{-1}) and SR 2014 (3.6 kg Nha^{-1}) seasons, plus the overall mean highest NUE was observed in FYM under tied ridge plots. Application of FYM in combination with CAN and tied ridges seemed to be the best bet for increased maize yields through enhancing both NUE and WUE.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYNONYMS

AE	- Agronomic efficiency
ASAL	- Arid and semi-arid lands
IE	- Internal utilization efficiency
NUE	- Nutrient Use Efficiency
PE	- Physiological efficiency
PFP	- Partial factor productivity
RCBD	- Randomized complete block design
RE	- Apparent crop recovery efficiency
RWH	- Rainwater harvesting
SSA	- Sub-Saharan Africa
WAP	- Weeks After Planting
WUE	- Water Use Efficiency

OPERATIONAL DEFINITION OF TERMS

ASAL is an acronym for Arid and Semi-Arid Lands, which are regions with low rainfall, high temperatures, and sparse vegetation.

Evapotranspiration is the total movement of water from the Earth's surface to the atmosphere, through both evaporation (from soil and water bodies) and transpiration (water released by plants).

Food security is when all people, at all times, have access to enough safe, nutritious food that meets their dietary needs and preferences for a healthy living

Moisture deficit is a condition where the amount of water needed by an area for plant growth and other processes exceeds the amount of water available.

Nitrogen use efficiency is the ratio of the nitrogen in a crop's yield to the nitrogen inputs, representing how effectively a plant uses applied nitrogen for growth

Nutrient depletion is the loss of essential nutrients from a system, through processes such as continuous cropping or erosion leading to a decline in fertility

Water use efficiency measures the yield or biomass output obtained per unit of water consumed by a plant

CHAPTER ONE

INTRODUCTION

1.1 Background information

Globally, water and nitrogen availability remain the most restraining factors for the growth of crops (Gikonyo *et al.*, 2022). Approximately 80% of the cultivated land is rain-fed, and it contributes at least two-thirds of the world's food production (Oduor *et al.*, 2020a) infrequent and unpredictable rainfall patterns, coupled with deteriorating soil fertility continue to ravage rainfall-dependent agriculture globally (Oduor *et al.*, 2021). This is regardless of the anticipated surge of 60% in global food demand by 2050 compared to 2007, with the escalation in sub-Saharan Africa (SSA) expected to be greater (Van Ittersum *et al.*, 2016). This is further exacerbated by the ever-increasing population (Njenga *et al.*, 2021).

In Sub-Saharan Africa (SSA), farming production occupies more than 95 % of the arable land and is primarily rain-fed (Mutuku *et al.*, 2020). This very land is vital for food security and livelihood strategies for more than 80 % of the inhabitants in the region (Serdeczny *et al.*, 2019). However, the fluctuating climatic patterns, characterized by inconsistent rainfall, extended dry spells, and frequent droughts, have led to reduced productivity, unpredictable yields, and crop failure (Oduor *et al.*, 2021). Nevertheless, all is not doom and gloom. With improved management, there is a reason to believe that there is light at the end of the tunnel and that agriculture in the ASALs can still be made more productive.

The economy of Kenya depends on agriculture of which maize contributes significantly to food security (Wandaka, 2016). When it comes to the most vital cereal crops worldwide, maize is ranked after wheat and rice (Meena *et al.*, 2018). Maize is an imperative crop for food security in Kenya with 90 % of the population ingesting it as a staple food (Ochieng *et al.*, 2017). It directly contributes 26 – 27% of the Gross Domestic Product (GDP) (Velesi, 2018). Approximately 40 % of the total crop area in Kenya is under this cereal (Naseem *et al.*, 2018). Production of maize is predominantly by small-scale farmers (Wambugu *et al.*, 2012) who contribute approximately 70% of the total maize production in the country (Onono *et al.*, 2013) These farmers hinge on agriculture for income but have inadequate resources to invest in it. (Mutuku *et al.*, 2020).

Its production in Kenya is majorly rain-fed, with rainfall patterns and soil composition as major determinants (Velesi, 2018). Apart from water stress and low soil fertility, other challenges such as poor tillage practices and extension services and even fluctuation of market prices its production fluctuates each year depending on farming practices and climatic conditions However, its production fluctuates annually depending on farming practices and climatic conditions (Onono *et al.*, 2013) .Case in point is when maize yield rose significantly from 39 million bags in 2014 to 42.5 million bags in 2015. This gave hope to the country that it would be self-sufficient in maize and that the prices would stabilize throughout 2016 and 2017 (Economic Survey 2016 - Kenya National Bureau of Statistics). Nevertheless, it happened in the contrary as the prices continued to escalate because of a structural production deficit. Consequently, the government had to import maize and provide subsidized maize flour to cushion consumers.

Agriculture, a key socio-economic activity in Kenya, is affected by climatic conditions (Malhi *et al.*, 2021). The ASALS are the most hit by climate change, and they make up 89% of the country's dry land, which accounts for 23 out of 47 Counties in the country (Akuja & Kandagor, 2024). Just like most areas in Kenya, maize production in Eastern Kenya is rain-fed despite the rains being inadequate, short duration, poorly distributed and highly variable within seasons (Wamari *et al.*, 2012). The low and poorly distributed rains, high evapotranspiration and declining soil characteristics have been listed as major causes of low maize production in ASALs (Karuma *et al.*, 2016). Scholars like (Karuma *et al.*, 2016) reported that the amount of rainfall is not the limiting factor to crop production, but rather rainfall variability, high intensities, reduced or few rain events and poor spatial and temporal distribution.

Crop production in semi-arid areas like Machakos is influenced primarily by rainfall and soil fertility (Karuku *et al.*, 2019). Extreme rainfall variability, characterized by a shortage of its supply and distribution, have a direct impact on soil productivity as it affects runoff and soil water holding capacity (Okeyo *et al.*, 2014). These could possibly influence people's livelihoods since they depend on rain-fed agriculture leading to food insecurity (Omoyo *et al.*, 2015). There is therefore need to embark on practices that improve plant nourishment and soil water-holding capacity through reduced runoff (Okeyo *et al.*, 2014).

Even though there may be good rainfall distribution occasionally, crop harvests may still be hindered by poor agronomic practices (Mupangwa *et al.*, 2012). Soil tillage is a significant factor in maize production as it contributes up to 20% of crop yields (Alam *et al.*, 2014). When organic inputs are applied under tillage-based systems, the organic

matter increases soil moisture retention (Kiboi *et al.*, 2019). Soil tillage can remarkably influence dynamics of nitrogen in the soil by creating an impact on aeration of soil, microbial activities, decomposition of organic matter (OM) and availability of nutrients (Wasaya *et al.*, 2017) . In order to safeguard the long-term productivity of the soils, farmers have adopted soil and water conservation strategies to reduce soil erosion and conserve soil moisture (Rotich *et al.*, 2022) . Tied ridges together with soil fertility and other water maintenance practices can curb soil moisture stress and improve crop productivity (Zhao *et al.*, 2018).

A number of measures have been embraced to ensure food security in Kenya and Africa as a whole. Soil moisture conservation and combined use of organic and inorganic fertilizers are among the strategies adopted to improve production. Therefore, nutrient and water have to be managed properly in order not only to produce sufficient food but also to sustain farmers' livelihoods (Alemu *et al.*, 2024). This study thus sought to assess the interaction effect of tied ridging and fertilizer use on NUE and WUE of maize grown in a semi-arid environment.

1.2. Statement of the problem

Agricultural land in sub-Saharan Africa (SSA) faces immense pressure struggling to feed approximately 950 million people (DESA, 2017) which is expected to reach 9.73 billion by 2050 (Ekpa *et al.*, 2018). This challenge is worsened by continuous soil fertility degradation and the escalating impacts of climate change, which severely limit the land's ability to provide sufficient food (Descheemaeker *et al.*, 2016). The Montpellier Panel Report, (2015) further stated that by 2050, climate alteration will perhaps increase starvation and child malnourishment in SSA by as much as 20 %,

undermining past progress achieved through the Millennium Development Goal (MDG) and jeopardizing the success of the Sustainable Development Goals (SDGs). The region's food insecurity was already at 23% in 2013, with a staggering 32.4% of children experiencing stunted growth by 2020. Urgent and sustainable agricultural interventions are critical to reverse these alarming trends and safeguard food security for masses (World Bank, 2021)

In the ASALS, agricultural productivity is severely hampered by inadequate and highly variable precipitation alongside inherently low soil fertility (Drechsel *et al.*, 2015). Projections reveal rainfall pattern in SSA region could reduce by 10 % in 2050, significantly reducing surface drainage by 17 % particularly in regions receiving 1000mm per year, whereas in regions receiving less than 500mm per year, surface drainage would be cut by 50% (Papa *et al.*, 2023). In many areas with low and erratic rainfall, crops face significant stress from both scarce and unpredictable rainfall and widespread nutrient deficiencies, with the latter often being the second most limiting factor. These two challenges are intrinsically linked: water availability impacts nutrient uptake, while nutrient levels influence a crop's ability to absorb water and withstand drought. Therefore, overcoming these constraints necessitates integrated management involvements that address both soil water and nutrient limitations simultaneously.

Maize availability directly underpins Kenya's food security, highlighting the urgent need to boost its production (Namikoye *et al.*, 2015). A food security assessment report by the Ministry of Agriculture in 2013 stated that cyclonical droughts experienced in the country, especially in Eastern region have severely hindered efforts to improve food security state of affairs in the country. For instance, farmers in Machakos County,

achieve significantly lower maize yields (barely 1 t/ha) compared to the over 2.0 t/ha gotten from research stations and commercial farms, underscoring a substantial yield gap that must be closed (Kwena *et al.*, 2018).

Machakos County, a semi - arid region, grapples with scarce and unpredictable rainfall, leading to severe soil moisture deficits. This challenge is compounded by inherently low soil fertility, particularly a deficiency in crucial plant nutrients like nitrogen and phosphorus (Kwena *et al.*, 2018). Consequently, ensuring adequate crop nutrition is paramount for food security in this area. Addressing food insecurity in Machakos County therefore demands a dual approach: tackling both water deficits and soil nutrient depletion simultaneously.

1.3 Justification

Water and nutrients are crucial, interdependent inputs in crop production yet they are frequently limited by physical or economical constraints (Drechsel *et al.*, 2015). Water is an important factor for crop production and its shortage directly reduces agricultural productivity. It is therefore necessary to enhance crop production with minimal water usage (Rahman *et al.*, 2017). In order to attain food security in regions where water is limited and rainfall poorly distributed, one needs to focus on how to maximize yield per unit of water (water use efficiency) rather than per unit of land (Wadzanayi & Stroosnijer, 2014). Water Use Efficiency (WUE) is simply how well plants utilize water to produce yield (Koech & Langat, 2018). It defines the ability of plants to tolerate limited water availability (Ullah *et al.*, 2019).

In order to respond to the increasing water scarcity, enhancing agricultural WUE is key (Drechsel *et al.*, 2015). For slight additional water to increase yields in dry regions, hindrances to efficient water use must be adequately addressed (Drechsel *et al.*, 2015). This calls for strategies to deal with fluctuating climatic conditions, using efficient and cost-effective soil water conservation options (Zougmor'e *et al.*, 2014).

Water conservation is a crucial need in ASAL regions, and tied ridging has come out as one of the most effective management practices. It considerably improves soil moisture storage, reduces runoff and boosts water infiltration and rainwater holding capacity in the fields (He & Wang, 2019). Tied ridging helps crops make better use of both water and nutrients by preserving more water in the soil.

NUE is the ability of crops to absorb and make use of nutrients for biomass or grain production and is closely tied to soil water availability (Liang *et al.*, 2024). For instance, for nitrogen to improve yield in ASALs, sufficient soil moisture is paramount. Otherwise, using it alone during dry periods has a limited effect (Drechsel *et al.*, 2015).

These interconnections therefore create a need to increase both WUE and NUE simultaneously, especially under conditions of soil degradation and water scarcity (Tefera *et al.*, 2024). Managing one without the other would probably limit productivity (Mutuku *et al.*, 2020). In the pursuit to come up with management schemes that target sustainable yields, as well as improved water and nutrient use efficiency in water-stressed regions, understanding the interaction effects of soil water and nitrogen is crucial.

While many studies on tied-ridging have concentrated on its influence on crop yield, fewer have examined its direct effects on soil water status, WUE or NUE or on both WUE and NUE (Wafula 2022) highlighting a research gap that deserves attention.

1.4 Conceptual Framework

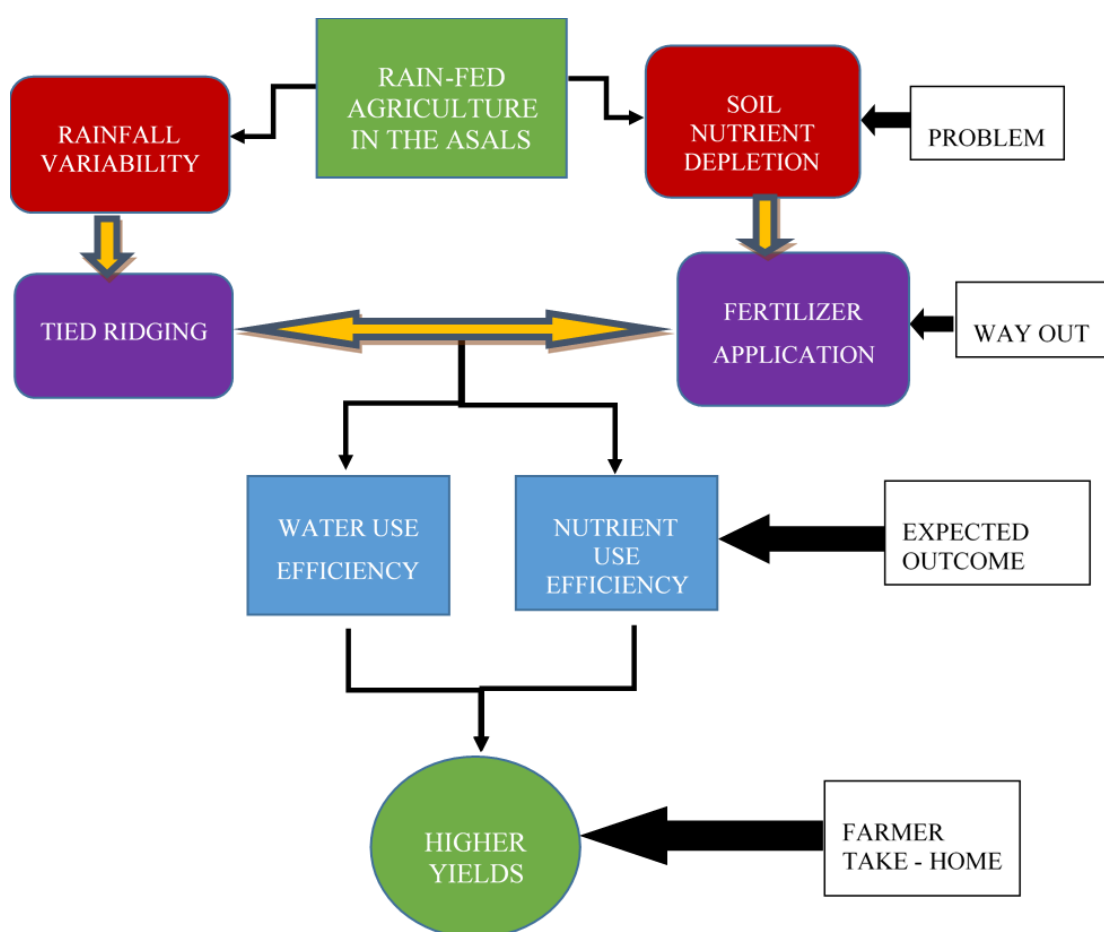


Figure 1: Conceptual Framework (Source: Author, 2014)

1.5 Research objectives

1.5.1. General objective

To establish whether combined tillage and nutrient management practices can improve maize productivity in ASALS.

1.5.2. Specific objectives

The specific objectives of the study were: -

- i) To find out whether tied ridging and fertilizer application can enhance maize grain yield in Katumani, Machakos County.
- ii) To find out whether tied ridging and fertilizer application can enhance water use efficiency (WUE) of maize in Katumani, Machakos County.
- iii) To find out whether tied ridging and fertilizer application can enhance nitrogen use efficiency (NUE) of maize in Katumani, Machakos County.

1. 6. Null Hypothesis

H₀₁: Tied ridging and fertilizer application has no effect on maize yield.

H₀₂: Tied ridging and fertilizer application has no effect on WUE of maize.

H₀₃: Tied ridging and fertilizer application has no effect on nitrogen use efficiency of maize.

CHAPTER TWO

LITERATURE REVIEW

2.1 Challenges experienced by soils in Eastern Kenya

Soils in the Eastern Kenya ASALs are vastly weathered, with minimal organic matter content and are less fertile (Recha *et al.*, 2013). Topography of the land and excessive vegetation clearing make the soils predisposed to soil erosion, leading to low aggregate stability (Sennhen, 2015). Soil erosion also makes fertilizer application expensive, as it is rendered useless, hence re-applying becomes a necessity (Recha *et al.*, 2013).

Hardpans, a common scenario with the ASAL soils, is brought about by soil aggregates being crushed to fine aggregates, which, with time, join and form a seal of impermeable layer restricting rainwater infiltration (Kathuli & Itabari, 2014). As a result, rainwater is lost through runoff, carrying away the top fertile soil essential for vigorous crop growth (Musyimi *et al.*, 2022). The increased soil erosion, moisture deficits, depleted soil fertility, with soil crusting and compaction, impede crop production in ASALS (Karuma *et al.*, 2014).

2.2 Conservation of soil moisture in the ASALS

Moisture conservation is an important management approach for crop and fodder yield in ASALS (Karuma *et al.*, 2016). An effective moisture conservation technique to be adopted in ASALS should be one which improves rainfall infiltration and ensures adequate soil moisture retention for crop production (Njeru *et al.*, 2013).

Crop production in the ASALS can be improved through rainwater harvesting (RWH) and soil fertility management measures. Rainwater harvesting methods are categorized into two, namely, ex situ and in situ RWH. Ex situ RWH involves capturing rainwater outside the farm. Rainwater is collected and stored in natural or man-made reservoirs such as ponds, wells, small earth dams and other cisterns of different sizes *for* supplemental irrigation (Tefera *et al.*, 2024).

In-situ rainwater harvesting technologies such as zai pits, mulch ripping, earth and stone bunds, furrow and tied ridges have been suggested as the technologies that are effective in increasing crop production (Koreeny, 2022). These ones capture and utilize rainwater within the farm (Tefera *et al.*, 2024). They are simple and more affordable technologies that trap and hold rainwater where it falls long enough, increasing time for infiltration, delaying the occurrence of severe water stress, thus buffering crops against damage resulting from water deficits (Mudatenguha *et al.*, 2014). Combining water harvesting technologies with fertilizer inputs creates a synergy that increases water and nutrient use efficiency, hence increasing yield (Wafula, 2022)

2.3 Conserving soil moisture by using tied ridges

Tied ridging is among the most sustainable soil and water conservation techniques advocated for in semi-arid areas (Murungu, 2012). This is a form of micro-basin tillage, also called furrow diking, boxed ridging or basin tillage (Wanjala, 2024) . In this technique, crops are grown on small ridges on the contour while blocking the furrows with cross-ties to retain rainwater for infiltration. Comparison has been done on different water harvesting techniques (i.e., level basin, tied ridges and conventional

tillage) for their water retention, availability and suitability to crop production. Results from the tied ridges techniques have given superior yields for different crops (Miriti *et al.*, 2013). However, tied ridging is also reported to give contradictory results, as the net effects of tied ridging can either be positive or negative.

When evaluating tied ridges, one has to consider soil texture and rainfall regime. In East Africa, tied-ridges were successful at near normal rainfall (i.e., 500-600 mm), but mostly counterproductive above 700 - 900 mm due to anaerobic conditions in the rhizosphere and nutrient leaching (Jensen *et al.*, 2020). The land on which it is used should have a slope that is less than 2% to ensure furrows retain rainwater by avoiding loss through runoff (Kathuli & Itabari, 2014).

Application of the tied-ridge technique ensures moisture retention is improved and reduces the negative effects of intra-seasonal dry spells that frequently lead to low productivity and crop letdown (Karuma *et al.*, 2012). The ridges concentrate water in the furrow bottom and near the root zone, reducing runoff within the fields. Ridging ensures water infiltration and increased root depth (Recha *et al.*, 2013). Miriti *et al.*, (2012) reported greater crop yields in tied ridges relative to the normal farming practice in Kenya. Jensen *et al.*, (2020) reported enhanced crop response to rainfall and fertilizer as a result of ridging. Apart from it increasing soil surface roughness, tied ridging has also been stated to capture rainfall and increase infiltration rate, thus storing more soil water and availing it to crop resulting in higher crop yields (Wanjala, 2024). Now that tied ridging is not mechanized, farmers face the challenge of requiring high labour (Miriti *et al.*, 2013).

Generally, conservation of soil moisture increases water productivity by reducing both runoff and evaporation, a condition that improves storage of soil water (Murungu, 2012). This makes it a vital management practice in semi-arid regions (Karuma *et al.*, 2012).

2.4 Management practices for soil fertility

Fertility of the soil comes second, after water availability, as a factor limiting crop production in semi-arid areas (Naorem *et al.*, 2023). Soil fertility depletion is reported as a major setback in crop production in Sub-Saharan Africa (Chirere, 2016). Poor soil fertility contributes to the low crop yield, but with appropriate fertilizer application, production is increased (Ademba *et al.*, 2015). The poor soil fertility and nutrient depletion are predominantly attributed to the continuous cultivation of high nutrient-demanding crops such as maize on the same pieces of land without or with minimal nutrient returns (Deb *et al.*, 2023)

Using inorganic and organic fertilizers is a management option that improves crop production. Both of them, whether applied individually or in combination, have positive effects in supporting maize growth (Erhunmwunse & Olayinka, 2018). Inorganic (mineral) fertilizers are readily soluble in soil solution, less bulky and easy to manipulate but their constitution mostly consists of the macro nutrients unlike organic manures, which have both macro and micro nutrients (Musankindi, 2013). Farmers are discouraged by the fact that, other than it being expensive and inaccessible, inorganic fertilizers have been associated with greater soil acidity and nutrient imbalance (Adamu *et al.*, 2015). In Eastern Kenya, therefore, farmers prefer farmyard

manure since it is cheaper as opposed to the more expensive inorganic fertilizers (Karuku *et al.*, 2019). However, due to land scarcity, farmers keep very few animals, hence limited quantities of manure (Jaetzold *et al.*, 2007). In addition, the low quality of farm yard manure produced by farmers and the slow process of mineralization deems it necessary for manures to be applied at comparatively higher rates than the inorganic fertilizers in order to meet crop nutrient requirements (Ayoola & Adebayo, 2017). This necessitates a combined application as it gives the ultimate benefit in enhancing soil fertility and improving soil physical properties, thus, higher yields (Chivenge *et al.*, 2022).

2.5 Response of different developmental stages of maize to moisture deficit

In Sub-Saharan Africa, maize is the primarily cultivated cereal crop under rain-fed agriculture (Karuma *et al.*, 2016). Rainfall variability affects maize yields in two major ways. First of all, the influence of a certain rainfall variable is adjusted by the other. The daily, seasonal and yearly rainfall variations are significant in influencing the efficiency of maize development. Then we have the microclimate around the crop coming in second. The state of the water within the germination zone and very near the ground where the crop grows has a high consequence on crop performance (International Institute of Tropical Agriculture, 2004). Available rainfall determines maize establishment, especially during the early growth stages, since the reversible moisture-sensitive block preventing germination in drying soils causing the seeds to germinate in accordance to the rainfall patterns (International Institute of Tropical Agriculture, 2004). Any slight change in the rainfall pattern influences the germination process.

Maize responds differently to water stress at different developmental stages (Pritee *et al.*, 2014). Maize crop experiences thrilling sensitivity to water shortage during critical periods from flowering to the start of grain - filling phase (Sankaralingam *et al.*, 2025) This is the period during which the greatest leaf area index merges with the highest evaporative demand (Kogo *et al.*, 2021). At this point, when defining its major yield components, the number of ears in a single plant and number of kernels in an ear are essential.

2.6 Approaches to increasing Nitrogen use efficiency

The key objective of nutrient use is to enhance the wholesome production of cropping systems. This is through availing optimum nourishment to the crop while reducing nutrient losses from the field. NUE also supports agricultural system sustainability by contributing to soil fertility or other components of soil quality. The most appreciated impacts are those contributing towards complete cropping system performance. For that reason, it is vital to incorporate management options that improve NUE without decreasing productivity or prospective for future productivity (Alemu *et al.*, 2024). One important feature to enhancing N use efficiency is achieving synchrony of N delivery from soils, fertilizers and the plant's N uptake demand (Govindasamy *et al.*, 2023). Measures on how to manage and increase N use efficiency has been reported in many research findings including (Cassman & Dobermann, 2022).

2.7 Influence of soil fertility on WUE.

The utility of water and nutrient by plants are closely intertwined. For crops to make the most out of fertilizers, water must not be a restrictive factor, and vice versa. When

enough fertilizers are applied, not only do crop yields increase, but also WUE (Wang *et al.*, 2023). Fertilizers facilitates crops to grow bigger and develop a fuller canopy, which lessens evaporation and increases transpiration, resulting to higher WUE. Nitrogen fertilizers to be specific stimulates larger plant size, more leaf area and robust root systems. These deeper and wider roots allow plants to explore more soil layers and reach a larger pool of stored water (Thorup-Kristensen *et al.*, 2020) .Plants with fertilizer also tend to endure drought better (Wang *et al.*, 2023).Furthermore, addition of organic matter increases the soil water holding capacity, making moisture more obtainable for growth of plants (Thorup-Kristensen *et al.*, 2020).

On the other hand, low soil fertility can hinder how efficiently plants utilize water. In the African Sahel, for example, a mere 10 to 15% of rainfall is used for growth of plants, while the remaining percentage is lost through runoff, evaporation and drainage (Biasutti, 2019) .This is partially because nutrient- deficient roots are weak and cannot efficiently reach deeper water reserves.

2.8 Influence of water on NUE

Likewise, water availability also influences how efficiently plants use nutrients (NUE). Among the best ways to improve NUE is integrated soil and water management practices (Qiu *et al.*, 2025) . Effective conservation of water can augment the beneficial effects of fertilizer application (Drechsel *et al.*, 2015).Water supply increases fertilizer use efficiency by increasing nutrient availability to crops and hence its uptake (Abid *et al.*, 2012). Soil nutrients diffuse faster where water films are thick, because nutrient uptake relies on moisture availability (Ghosh *et al.*, 2018) . Furthermore, low soil moisture content hinders soil microbial activities as it inhibits nutrient release by

organic matter decomposition (Abid *et al.*, 2012). In conclusion, insufficient or delayed rainfall makes investment in fertilizer to be counterproductive hence both factors should be seriously considered by farmers.

2.9 Water and fertilizer concerted effort at the field and farm level

Water and nutrients work hand in hand when it comes to crop yield. More often than not, fertility of the soil limits productivity, especially in rain-fed farming systems. As a matter of fact, water and nitrogen can occasionally stand in for each other in boosting yields since with abundant water, less nitrogen may be needed and vice versa (Drechsel *et al.*, 2015). Having an adequate amount of soil moisture and nutrients supports healthy root growth, delays leaf aging and ensures proper grain filling, all of which contributes towards increased yield (Wu *et al.*, 2022)

In contrast, nutrient depletion and organic matter loss decreases soil infiltration and weakens development of roots, making it tougher for crops to access water, leading to lowers yields (Drechsel *et al.*, 2015). If rainfall is too low or unpredictable, fertilizers alone cannot boost productivity because the crops simply do not get enough water to utilize the nutrients effectively (Singh *et al.*, 2015) hence investing in fertilizers in the ASALS may not easily pay off.

It is also worth noting that nutrients in the soil is moved and distributed mainly through water and so nutrient uptake at the plant level will always be limited if the soil is under water stress. As Drechsel *et al.*, (2015) highlighted, soil fertility management must consider the strong interaction between water and nutrients.

2.10 Improving water use efficiency to enhance fertilizer efficiency

With the intention of improving crop water use efficiency of and total crop production, Drechsel *et al.*, (2015) proposed four objectives or approaches. These are; increasing transpirational crop water productivity, increasing the storage size of available water in space or time, increasing the proportion of non-irrigation water inflows and decreasing non-transpirational water outflows. Generally, the most essential approaches are likely those that trap water, avoid it from escaping the plant root zone and develop it for use by crops (tolerance).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

The experiment was done at KALRO – Katumani, National Dry Land Farming Research Centre, (1°35'S and 37°14'E), which is a gently slopy (1% slope) area. Machakos County falls under the upper midland 4 (UM 4) agro ecological zone, described as the sunflower-maize zone with a low potential for rain-fed agriculture (Jaetzold *et al.*, 2007).

It is a hot and dry region receiving bimodal (two-season) type of rainfall, with long rains spread from mid-March to May (MAM) with a peak in April while short rains begin from mid-October, peaking in November and ending in December (OND) (Jaetzold *et al.*, 2007). A dry spell between June and September separates the two rainfall seasons. Even though the short rains receive less amount of rainfall, they are more reliable because its more evenly distributed; hence more important for crop production (Kwena *et al.*, 2017). Long rains in the region are associated with crop failures due to the dry spells experienced, poor distribution, unreliability and inadequacy for crop production (Mbayaki & Karuku, 2021) Mid - season dry spells commonly occur in both seasons and pose a risk to crop production (Jaetzold *et al.*, 2007). Katumani station receives about 309.9mm and 298mm of rain during the MAM and OND seasons respectively (Huho, 2017).

Temperature and evaporation rates are generally high with February and September being the hottest months of the year. Minimum mean annual temperatures vary from 14°C to 22°C while maximum mean annual temperatures vary from 26°C to 30°C

(Jaetzold *et al.*, 2007) . Evaporation rates (ET^0) are high and exceed the amount of rainfall (r) except in November. Annual evapotranspiration is high and, the available rainfall is inadequate to meet this high evaporative demand (Kwena *et al.*, 2017).

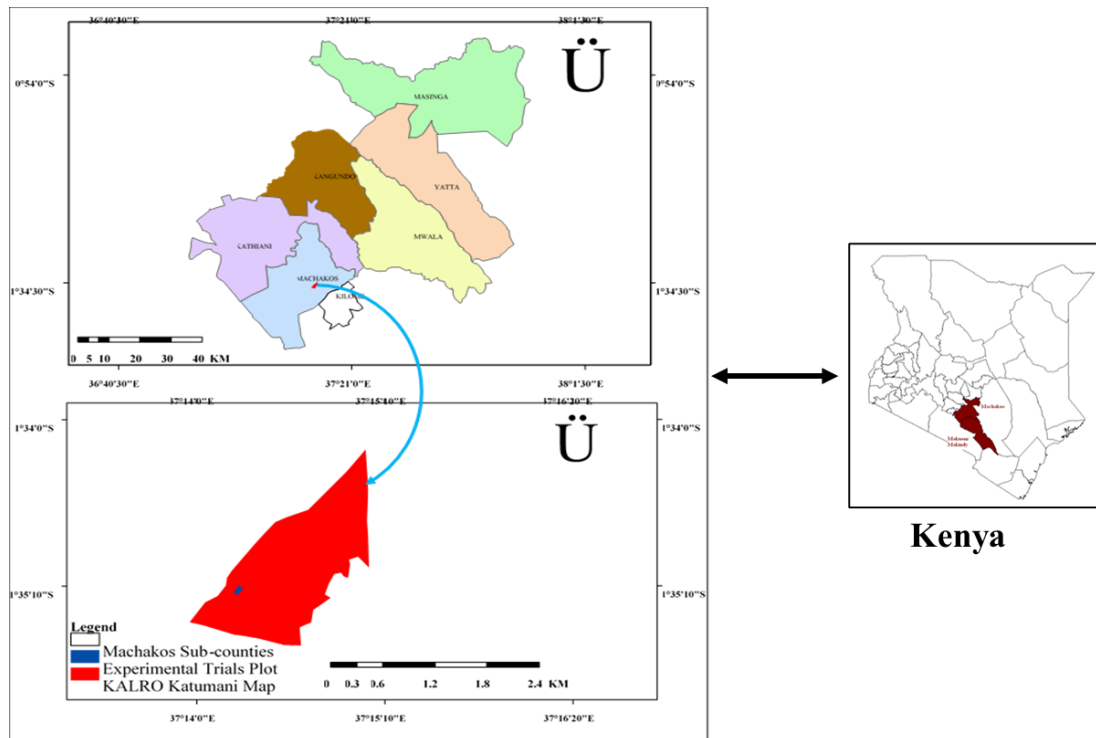


Figure 2: Study Site (Source: KALRO - Katumani)

3.2 Field Trial Structure

Field trials conducted at KALRO Katumani; Machakos County were set out in Randomized Complete Block Design (RCBD) in a $2 \times 2 \times 4$ factorial arrangement (Table1). The trial factors comprised two cropping seasons, short rains (SR) 2013& SR 2014), two moisture conservation techniques; tied (W0) and untied ridges (W1)) and

four fertilizer sources (F0, F1, F2, F3). The treatments as laid out in the field appeared as; Control, where no fertilizer was used (W0F0 and W1F0 plots), sole application of farmyard manure (FYM) (W0F1 and W1F1 plots), sole application of Calcium Ammonium Nitrate (CAN) (W0F2 and W1F2 plots) and combined use of CAN and FYM in the W0F3 and W1F3 plots. Both soil conservation techniques and fertilizer sources were replicated four times totaling 64 plots. Each plot measured 5.4m×3.6m and by a 1m strip while a 3m strip separated the blocks.

Table 1: Field Experimental Layout

REP 1	REP 2	REP 3	REP 4
W0F2	W1F0	W0F0	W1F2
W0F1	W1F3	W0F2	W1F1
W0F0	W1F1	W0F3	W1F0
W0F3	W1F2	W0F1	W1F3
W1F0	W0F0	W1F3	W0F2
W1F1	W0F2	W1F2	W0F1
W1F2	W0F3	W1F1	W0F3
W1F3	W0F1	W1F0	W0F0

Treatment description

W0 = No tied ridging (farmers' practice), W1 = Tied ridges,

F0 = Control (No N fertilizer), F1 = Manure (5tha⁻¹) only,

F2 = CAN (20 kg N ha⁻¹) only, F3 = Manure + CAN

3.3 Agronomic practices and management of the experiment

Preset experimental plots were cleared and land breaking done using a hand hoe. Tied ridges, a series of closely spaced rectangular depressions (basins), were installed during seedbed preparation (Appendix I). Spacing of the ridges was 90cm tied at 2.5m

intervals. Ridges were 30cm high and ties (cross ridges) 20cm high. Cross-ties were made lower than the ridges to act as spillways in the event of heavy rainfall in such a manner that if full, the overflow was within the furrows but not down the slope (Bekele & Chemed, 2022).

During the first season (SR 2014), the experimental plots were prepared in October and planting done in November from 5th to 12th the same year. Dry land maize (Katumani Drought Variety, KDV-1) developed by Kenya Agricultural and Livestock Research Organization (KALRO) scientists was used in the experiment owing to its good adaptability in the study area. The variety used is one which matures early, having a maturity duration of between 120 and 150 days and is highly capable of yielding under semi-arid conditions.

Phosphorus fertilizer in the form of Triple super phosphate (TSP 0 - 46-0) was applied per planting hole uniformly for all treatments at a level of 26 kg P/ha. Four weeks after planting, Calcium Ammonium Nitrate (CAN 27:0:0) was applied as a top-dress at a rate of 20 kg N/ha. Farmyard manure obtained from the research Centre was applied by spot placement method at a proportion of 5 t/ha during planting and mixed with soil to avoid direct contact with the seed (Appendix II). Planting of seeds was done at two per hole at an inter-row spacing of 90 cm and intra-row spacing of 30 cm. Thinning was later done to one plant per hole in order to reduce competition for nutrients and increase proper establishment. Weeding was done manually, first using a hand hoe after four weeks and subsequently by hand pulling.

3.4 Data collection

3.4.1 Rainfall measurements

During the study period, SR 2013 and SR 2014, daily rainfall data (mm) were obtained from the weather station in the research center using a standard rain gauge (1 m above ground). The monthly averages were then computed. The total amount of rainfall received per season was also calculated. The rainfall data was used to calculate of water use efficiency.

3.4.2 Soil sampling and analysis

A random collection of soil samples was done at 0 – 20 cm depth before planting. It was later composited to evaluate the physical and chemical status of the soil. Sampling was done after land preparation and just before planting. The soil analysis done included soil particle size, pH, available P, total soil N, total organic carbon and exchangeable cations (Mg, K, Ca). They were analyzed following (Okalebo *et al.*, 2002) manual.

a. Soil particle size analysis (hydrometer method)

This was done to estimate the percentage sand, silt and clay contents of the soil. Soil particle size analysis is often reported as a percentage by weight of oven-dry and organic matter-free soil. The analyses are usually performed on air-dry soil. Based on the proportions of different particle sizes, a soil textural category may be assigned to the sample. The first stage in a particle size analysis was the dispersion of the soil into the individual particles. These were the sand (2.00 - 0.05 mm), silt (0.05 - 0.002 mm) and clay (< 0.002 mm) fractions. Individual soil particles are often bound into aggregates, hence

the requirement for dispersion. The hydrometer method of silt and clay measurement relies on the effects of particle size on the differential settling velocities within a water column.

b. Soil pH

pH of the soil was determined by adding 50 ml of de-ionized water to 20 ± 0.1 g of 2mm sieved soil in a beaker. Stirring of the mixture was done for 10 minutes, allowed to stand for 30 minutes then shaken again for 2 minutes. A glass electrode on the pH meter was used to take the pH reading of the soil suspension.

c. Available phosphorus

Mehlich extraction was the method used to determine available phosphorus. The principle behind the method was to determine the relative bio-availability of ortho - phosphate ($\text{PO}_4\text{-P}$) in soils with acid to neutral pH and with low CEC ($<10\text{meq}/100\text{g}$). The M1 extracting reagent comprises of a mixture of 0.05 N HCl and 0.025 N H_2SO_4 , also referred to as 'dilute double acid' solution. In order to get rid of organic matter which would be responsible for interfering with colour formation, activated charcoal was added in the extracting soil solution. Ammonium molybdate - ammonium vanadate mixture is used to generate a yellowish colour of vanadate – phospho - molybdate complex which is measured spectrophotometrically at 430nm. 5 grams of soil were weighed and 25ml of extracting solution added to the soil into soil extraction bottles. It was later placed on to a mechanical shaker for 1 hour. The extract was filtered through a Whatman® filter paper mounted on a funnel into a collecting test tube. A clear filtrate was obtained. Colour development was done by pipetting 5 ml of filtrate into a test tube. 1 ml of ammonium vanadate - ammonium molybdate mixture was added and mixed using a vortex shaker (orbital shaker). KH_2PO_4 (100ppm) was used to prepare

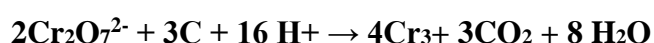
standard stock solution. The series 0 – 10 - 20 - 30 - 40 – 50 ppm were prepared by dilution of the stock solution. The working standards were fed into the spectrophotometer which generated an internal calibration curve upon which the analyte concentration in the sample was determined and given out in a read-out system.

d. Total nitrogen

The content of total nitrogen was measured in a digest obtained by treating soil sample with hydrogen peroxide + sulphuric acid, selenium and salicylic acid. The principle considered the possibility of losing nitrates when coupled with salicylic acid in an acid media formed 3-nitrosalicylic and or 4-nitrosalicylic. The compounds were reduced to their corresponding amino acid forms by the soil organic matter. The hydrogen peroxide oxidized the organic matter while the selenium compound performed as catalyst for the process and the digestion completed by H₂SO₄ at elevated temperatures.

e. Organic carbon

Organic carbon in the soil was determined using the principle of oxidation. The principle entails soil organic matter being titrated with concentrated sulphuric acid and aqueous potassium dichromate. Upon completion of the oxidation process from the heat of solution and external, the unused K₂Cr₂O₇ (in oxidation) was further titrated against ferrous ammonium sulphate. The used K₂Cr₂O₇, the difference between added and residual K₂Cr₂O₇, gave a quantity of organic C content of soil. The chemical reaction in the method is;



0.3g of ground (60 mesh) and digestion of air - dried soil was done using 5 ml potassium dichromate solution and 7.5 ml conc. H₂SO₄ in a pre - heated block digester at 145 - 155°C for exactly 30 minutes. The digest was removed and allow to cool. A 50 ml volumetric flask into which the digest was quantitatively transferred to was then topped up to 50ml mark using distilled water. 0.3 ml of Ferroin indicator solution and stirred using a magnetic stirrer, to ensure good mixing. Ferrous ammonium sulphate solution was used to titrate the digest; with a change of colour from green to brown marking the endpoint.

$$\text{Organic carbon (\%)} = \frac{T \times 0.2 \times 0.3}{\text{Sample weight}}$$

f. Exchangeable cations (K, Ca, Mg)

An excess of 1 M NH₄OAc (ammonium acetate) solution was used during extraction, such that there was a maximum exchange between NH₄⁺ and cations that initially occupied exchange sites on the soil surface. Flame photometry was used to ascertain the amounts of exchangeable sodium (Na) and potassium (K), while atomic absorption spectrophotometry (AAS) determined the calcium (Ca) and magnesium (Mg) in the extract. A releasing agent, Lanthanum or strontium, was added as to prevent formation of refractory compounds, which could have hampered with the determinations (e.g., phosphate).

3.4.3 Analysis of farm yard manure

The manure used during the study was examined for organic carbon, total N, pH, available P and exchangeable cations (Ca, Mg, and K) according to the procedures outlined by (Okalebo *et al.*, 2002) .For manure analysis, the samples were determined by the digestion

method, where digestion is carried out in tubes with sulphuric acid-salicylic acid-hydrogen peroxide and selenium. Total N was then measured by distillation and then titration with standard 0.01 NHCl, phosphorus was determined calorimetrically on a spectrophotometer. Potassium was measured by using by flame photometer, while an Atomic Absorption Spectrophotometer (AAS) was used to determine calcium and magnesium levels (Itabari *et al.*, 2013). The FYM used had high contents of essential P, K, Ca and Mg but had low N content and acidity (Table 2).

Table 2: Nutrient levels of farm yard manure used during the experiment

Description	O.C (%)	N	pH	P (ppm)	K (Cmolc kg ⁻¹)	Ca (Cmolc kg ⁻¹)	Mg (Cmolc kg ⁻¹)
Short rains	7.4	1.26	8.96	78.5	13.5	18.5	8.5

*All analytical procedures were adopted from Okalebo *et al.*, (2002)

3.5 Maize grain yields

Harvesting was at physiological maturity when the maize stalks were completely dry within an effective harvesting area of 3.4 m x 1.6 m from each plot, discarding the outer rows from either side to eliminate border effects (Appendix III). Fresh weight of the aboveground biomass of the maize plants was recorded. Ears (maize cobs with grains) were separated from the entire biomass (stovers), and the fresh weight was recorded. Both stovers and ears were dried and their dry weights recorded. The ears were later hand-shelled, and dry grain weight was recorded for grain yield computations.

3.6 Soil moisture content measurements.

During the start of the experiment, soil cores were taken to a depth of 20 cm from three randomly selected plots for the determination of bulk density. The soil cores were dried in an oven at 105°C for 48h (Jabro *et al.*, 2021). Bulk density was then calculated following the procedures as outlined by ((Okalebo *et al.*, 2002) according to Equation (Eq.1):

$$\rho_b = m/v \quad \text{Eq.1}$$

Where:

ρ_b = bulk density of the soil (g cm⁻³),

m = dry weight of the soil (g),

v = sample volume (cm³).

Thereafter, gravimetric water content was determined from core samples using equation (Eq.2):

$$\Theta_g = \frac{(W_{wet} - W_{dry})}{W_{dry}} \quad \text{Eq.2}$$

Where:

Θ_g = gravimetric water content,

W_{wet} = weight of the wet soil sample (g),

W_{dry} = weight of the dried soil sample (g).

Volumetric soil water content, defined as the volume of water per unit volume of soil was computed by multiplying the obtained gravimetric water content by relative bulk density (ratio of bulk density of soil to the density of water (1 cm³), using equation (Eq.3) as stated in (Miriti *et al.*, 2012b):

$$\Theta = \omega * (\rho_b \div \rho_w) \quad \text{Eq. 3}$$

Where:

Θ - volumetric water content (m^3 water/ m^3 soil),

ω - gravimetric water content (kg water/kg soil),

ρ_b - soil bulk density (g cm^{-3}),

ρ_w - water density (g cm^{-3})

Soil moisture content was monitored using a neutron probe moisture meter, CPN 503-DR. Using an auger, access tubes were installed in each of the sub-plots before planting. The depth of interest was 0–20cm owing to the concentration of active roots at this level. The neutron probe readings (neutron counts) were recorded fortnightly for SR 2013 and every 3 weeks for SR 2014. A graph of neutron counts against volumetric readings (obtained above) was plotted to develop a line of best fit with the equation:

$$y = mx + c$$

Where:

y – gravimetric water content,

m - gradient,

x - is the neutron counts and

c is the **y-intercept**, in this case, zero interception.

Thereafter, all the neutron probe readings at the experimental site were multiplied by the m gradient obtained to convert to volumetric water content.

3.7 Water use efficiency computation.

The amount of carbon assimilated as biomass or grain produced per unit of water used by the crop in the form of evapotranspiration (ET) is what defines water use efficiency. ET is the sum of water loss by evaporation from the soil and transpiration through the canopy. ET was quantified using the hydrological method. It is founded on the principle

of conservation of mass and estimated as described in Equation 4 (Eq.4) (Raes & Munoz, 2009):

$$\mathbf{ET} = (\mathbf{P} + \mathbf{I} + \mathbf{C}) - (\mathbf{D} + \mathbf{R}) - \Delta\mathbf{S} \quad \mathbf{Eq.4}$$

$$\Delta\mathbf{S} = \mathbf{S}_{\text{initial}} - \mathbf{S}_{\text{final}}$$

Where:

P is precipitation,

I is irrigation (There was no irrigation as the experiment was rain-fed)

C is upward flow into the root zone (The upward flow into the root was negligible)

D is drainage (There were no heavy rains or water logging drainage was insignificant)

R is runoff (Runoff was never observed as the experimental field was relatively flat)

$\Delta\mathbf{S}$ is the change in soil water content within the root zone at sowing ($\mathbf{S}_{\text{initial}}$) and at harvesting ($\mathbf{S}_{\text{final}}$) (Wang & Shangguan., 2015)

Consequently, ET was reduced to:

$$\mathbf{ET} = \mathbf{P} - \Delta\mathbf{S}$$

Water use efficiency was calculated using the equation (Eq.5) described (Zhang *et al.*, 2021).

$$\mathbf{WUE} = \frac{\mathbf{Grain\ Yield(Kgha^{-1})}}{\mathbf{ET\ (mm)}} \quad \mathbf{Eq.5}$$

3.8 Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) is the ratio between N removed in harvest products (N outputs or N yield) divided by the sum of all inputs to a cropland (Y. Q. Zhang *et al.*, 2015). It is crucial to highlight that NUE measures are not measures of nutrient loss

since nutrients can be held into the soil, and systems with relatively low NUE may not essentially be detrimental to the environment, while those with high NUE may not be innocuous (Drechsel *et al.*, 2015). It reflects on the direct production impact of applied fertilizer. The calculation of Agronomic NUE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. NUE is calculated as yield rise per unit of nitrogen applied using the equation:

$$NUE = \frac{Y - Y_0}{F}$$

Eq.6

Where;

Y = yield of a harvested portion of the crop with nutrient applied (kg ha⁻¹)

Y_0 = yield with no nutrient (N)+ applied/control yield (kg ha⁻¹)

F = amount of nutrient (N) applied (kg ha⁻¹)

3.9 Statistical analysis

Analysis of variance was executed on soil moisture, maize grain yield and water and Agronomic Nitrogen Use Efficiencies using the 14th edition of GENSTAT statistical software. Treatments with significant differences were separated using Tukey's 95% confidence intervals. The statistical model for the experiment was:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \gamma_k + (\alpha\beta)_{ij} + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + \delta_{ijk} + b_l + \epsilon_{ijkl} \quad \text{Eq. 7}$$

Where;

μ is the average,

α_i is the effect of level i^{th} of the season factor,

β_j is the effect of level j^{th} of the ridge factor,

γ_k is the effect of the k^{th} level of the fertilizer factor,

$(\alpha\beta)_{ij}$ is the interaction factor between level i of the season factor and level j of the ridging factor,

$(\alpha\gamma)_{ik}$ is the interaction factor between level i of the season factor and level k of fertilizer factor,

$(\beta\gamma)_{jk}$ is the interaction factor between level j of the ridging factor and level k of fertilizer,

δ_{ijk} is the interaction between level i of the season factor, level j^{th} of the ridging factor and level k of fertilizer factor,

bl is the block effect and

ϵ_{ijkl} is the experimental error on each plot

CHAPTER FOUR

RESULTS

4.1 Soil characterization

Soils in Katumani are predominantly chromic Luvisols (WRB, 2022). They also have a sandy clay loam texture at the 0 – 20cm depth surface with a dark red to reddish-brown hue (Sharma *et al.*, 2015). It was moderately acidic (pH 5.6) with low organic carbon (0.5 – 1.5%) and low phosphorus ($< 10\text{mg P kg}^{-1}$). It also had low nitrogen ($< 0.25\%$), exchangeable potassium and magnesium at 0.74 and 1.84 $\text{cmol}_c \text{ kg}^{-1}$, respectively. The levels of exchangeable calcium ions ($3.34 \text{ cmol}_c \text{ kg}^{-1}$) were moderate (Table 2).

4.2 Rainfall distribution during the period of study

The quantity and distribution of rain showed large differences between the two seasons during the study period (Figure 1). Cumulative seasonal rainfall in SR 2013 (347.1mm) was higher than in SR 2014 (209.3mm), representing a 39.7% decline and a cumulative seasonal difference of 137.8 mm. Rainfall events for SR 2013 and SR 2014 occurred in 35 and 30 days, with a cumulative dry spell of 81 and 86 days, respectively. Dry spell days for both seasons were approximately 3 times the number of rainy days, hence uneven distribution. However, the distribution was more or less the same. We had rain from the 1st week to the 6th week after planting, after which there was hardly any or no rain at all till the 13th week. The dry spell recurred on the 15th and 16th WAP. The single rainfall event with the highest rainfall amount during the SR 2013 was 119 mm, happening on the 4th week after planting (WAP), while in SR 2014 season, this was

experienced 14th WAP (70.9mm). Both seasons had intra-seasonal drought periods occurring at different times between the 7th and 12th WAP.

Table 3. Physico-Chemical Properties of Soils from the Study Site at 0-20cm Depth

	Measured values	Reference values	Interpretation
pH (1:2.5 soil water)	5.60	5.0 – 6.0	Moderately acidic
Available P (mg kg ⁻¹)	4.05	< 10	Low
Organic carbon (%)	0.78	0.5 – 1.5	Low
Total N (%)	0.18	0.12 – 0.25	low-moderate
K (cmol _c kg ⁻¹)	0.74	0.2 – 1.5	Moderate
Ca (cmol _c kg ⁻¹)	3.34	2 – 10	Moderate
Mg (cmol _c kg ⁻¹)	1.84	1 – 3	Moderate
Texture			
% Sand	56		
% Clay	32		
% Silt	12		
Textural class	Sandy clay loam		
Soil type (WRB, 2022)	Chromic Luvisols		

*All the interpretations are based on Appendix III

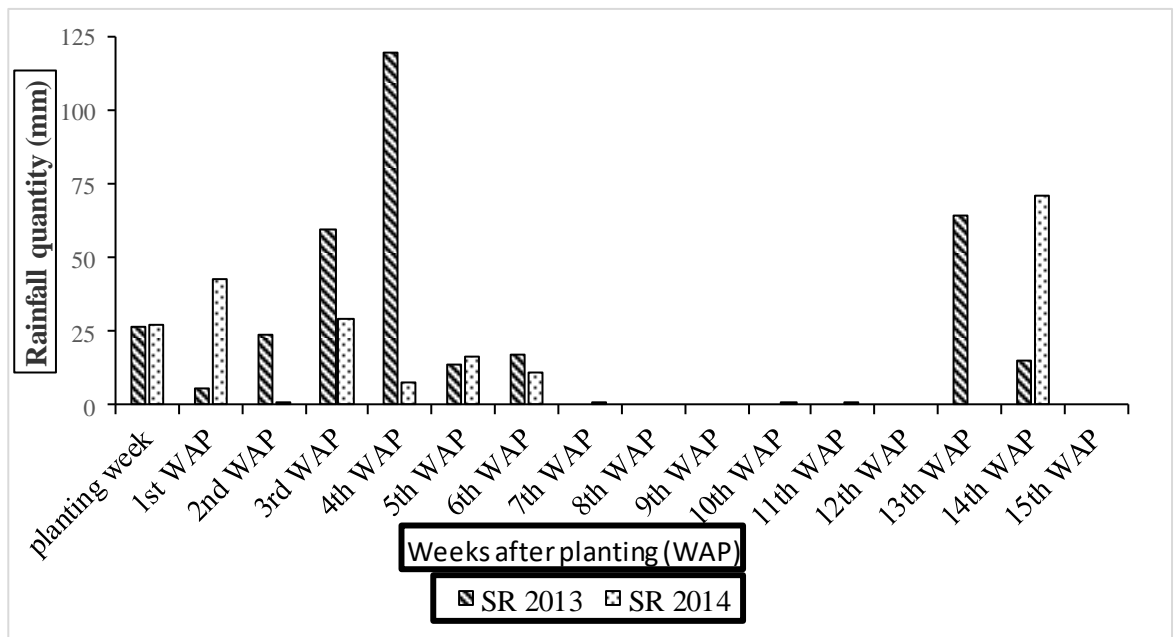


Figure 3. Amounts and distribution of rainfall during the study period

4.3 Soil moisture contents as influenced by tied ridging and fertilizer application

Generally, in both seasons, treatment combinations under untied ridges had more soil moisture than those in tied ridging (Figure 2). During 2013, tied ridging resulted in a lower soil moisture of 14.6% compared to 17.2% observed from plots without ridging (untied ridging). Likewise, in 2014 SR, moisture recorded from plots with tied ridges was 14.3% while from untied ridges was 17.5%.

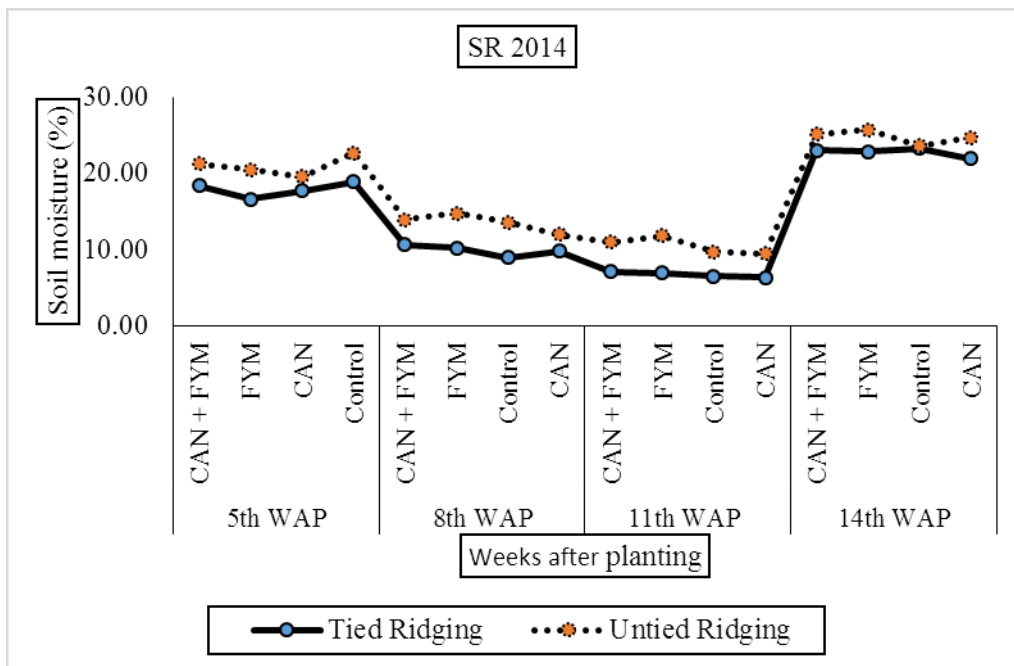
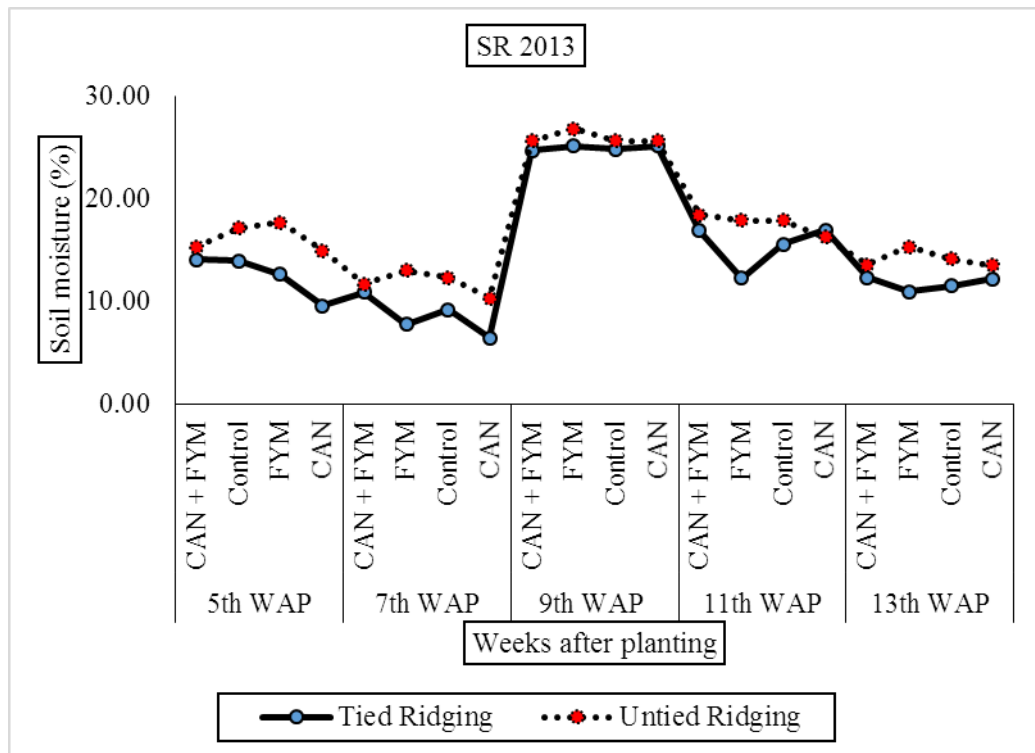


Figure 4. Soil moisture content (%) per treatment in weeks after planting (WAP)

4.4 Water use efficiency ($\text{kg ha}^{-1} \text{mm}^{-1}$) as influenced by tied ridging and fertilizer application

All the treatments and their interactions had a significant effect on WUE regardless of seasons (Table 4). Plots with tied ridges had higher WUE ($1.87\text{kg mm}^{-1} \text{ha}^{-1}$) compared to those with untied ridges ($1.00\text{kg mm}^{-1} \text{ha}^{-1}$). Plots with FYM ($2.08\text{kg mm}^{-1} \text{ha}^{-1}$) and FYM plus CAN ($1.76\text{kg mm}^{-1} \text{ha}^{-1}$) had higher WUE in comparison to the sole application of CAN ($1.02 \text{kg mm}^{-1} \text{ha}^{-1}$). Tied ridge plus FYM plots recorded the largest WUE ($3.23\text{kg mm}^{-1}\text{ha}^{-1}$) regardless of seasons. It was followed by TR+CAN+FYM ($1.86\text{kg mm}^{-1} \text{ha}^{-1}$), which was followed closely by sole CAN ($1.48\text{kg mm}^{-1} \text{ha}^{-1}$), and the least was TR+ Control ($0.89\text{kg mm}^{-1} \text{ha}^{-1}$).

Table 4. Table of means for WUE (kg mm⁻¹ ha⁻¹) of maize as influenced by tied ridging and fertilizer application

Moisture conservation	Fertilizer source	SR 2013	SR 2014	Moisture conservation *treatments
TIED RIDGES	Control	0.9 ^a	0.9 ^{ab}	0.9 ^{AB}
	CAN	1.5 ^a	1.5 ^{bc}	1.5 ^{BC}
	FYM	2.9^b	3.6^d	3.2^D
	CAN + FYM	1.5 ^a	2.2 ^c	1.9 ^C
Mean		1.7	2	1.9
UNTIED RIDGES	Control	1.4 ^a	0.3 ^a	0.8 ^{AB}
	CAN	0.6 ^a	0.5 ^a	0.6 ^A
	FYM	1.4 ^a	0.4 ^a	0.9 ^{AB}
	CAN + FYM	1.1 ^a	2.2 ^c	1.7 ^C
Mean		1.1	0.9	
GRAND MEAN		1.4	1.5	

SED

Season	0.608 ns
Ridging	<.001***
Fertilizer	<.001***
Season*Ridging	0.009**
Season*Fertilizer	<.001 ***
Ridging*Fertilizer	<.001 ***
Season*Ridging*Fertilizer	0.006**
% cv	7.6

SED- standard error of differences of means, **, ***significant at $p \leq 0.05$ and 0.001, **ns**- not significant. Means followed by the same superscript within a column are not significantly different at 5% alpha level. Small letters (a,b,c) are for individual treatments, while capital letters (A,B,C) are for the interaction effect (fertilizer*ridging)

4.5 Response of maize grain yield (kg ha⁻¹) to tied ridging and fertilizer application

SR 2013 yielded a higher 195kg ha⁻¹ as compared to SR 2014, having 128kg ha⁻¹ (Table 5), recording a 53% difference. Plots with tied ridges gave 45% more grain yield (191kg ha⁻¹) than untied ridges (132kg ha⁻¹). Plots with FYM had the highest yield, being 14% higher than CAN + FYM, 26 % higher than CAN alone and 28 % higher than Control. This work similarly revealed that integration of farmyard manure and tied ridging significantly increased grain yield by 34.24% (294kg ha⁻¹), as compared to the control (157.9kg ha⁻¹).

Table 5. Table of means for maize grain yield (kg ha⁻¹) as influenced by tied ridging and fertilizer application

Moisture conservation	Fertilizer source	SR 2013	SR 2014	Moisture conservation *treatments
TIED RIDGES	Control	157.9 ^{ab}	46.6 ^a	102.2 ^A
	CAN	200.7 ^{ab}	158.1 ^{ab}	179.4 ^{AB}
	FYM	322.3^b	265.9^b	294.1^B
	CAN + FYM	216.4 ^{ab}	158.6 ^{ab}	187.5 ^{AB}
Mean		224.3	157.3	191
UNTIED RIDGES	Control	183.8 ^{ab}	121.3 ^{ab}	152.6 ^A
	CAN	92.9 ^a	63.7 ^a	78.3 ^A
	FYM	237.1 ^{ab}	66.2 ^a	151.6 ^A
	CAN + FYM	148.3 ^{ab}	139.7 ^{ab}	144 ^A
Mean		165.5	97.7	132
GRAND MEAN		194.9	127.5	162
SED				
Season		0.002 **		
Ridging		0.005 **		
Fertilizer		0.005 **		
Season*Ridging		0.986 ns		
Season*Fertilizer		0.417 ns		
Ridging*Fertilizer		0.009 **		
Season*Ridging*Fertilizer		0.432 ns		
% cv		6.6		

SED- standard error of differences of means, **, ***significant at $p \leq 0.05$ and 0.001 , **ns**- not significant. Means followed by the same superscript within a column are not significantly different at 5% alpha level. Small letters (a,b,c) are for individual treatments while capital letters (A,B,C) are for the interaction effect

4.6 Nitrogen use efficiency as influenced by tied ridging and fertilizer application

The NUE values were 125 % higher in tied ridging ($3.75 \text{ kg grain}^{-1} \text{ kg N}^{-1}$) than for untied ridges ($-0.75 \text{ kg grain}^{-1} \text{ kg N}^{-1}$). NUE was 6.0, 6.6 and 1.3 kg of maize grain for each kilogram of nitrogen applied at 20 (FYM), 63 (CAN+ FYM) and $83 \text{ kg ha}^{-1} \text{ N}$ (CAN), respectively. Interaction between ridging and fertilizer source was also observed with FYM ($5.12 \text{ kg grain}^{-1} \text{ kg N}^{-1}$) and CAN ($4.72 \text{ kg grain}^{-1} \text{ kg N}^{-1}$), both under tied ridging, having the highest NUE. A negative NUE ($-3.569 \text{ kg grain}^{-1} \text{ kg N}^{-1}$) was observed when CAN was applied without ridging (Table 6). Plots with FYM recorded the highest NUE at $3.05 \text{ kg grain}^{-1} \text{ kg N}^{-1}$, a 54% increment as compared to treatments with CAN + FYM ($0.89 \text{ kg grain}^{-1} \text{ kg N}^{-1}$) and 74 % higher than CAN alone ($0.58 \text{ kg grain}^{-1} \text{ kg N}^{-1}$).

Table 6. Nitrogen use efficiency of maize as influenced by tied ridging and fertilizer application

Moisture conservation	Fertilizer source (kgNha⁻¹)	SR 2013	SR 2014	Moisture conservation *treatments
TIED RIDGES	CAN (20)	6.0 ^d	3.4 ^c	4.7 ^C
	FYM (63)	6.6^d	3.6^c	5.1^C
	CAN + FYM (83)	1.3 ^{bc}	1.5 ^b	1.4 ^B
Mean		4.6^b	2.9^b	3.8^B
UNTIED RIDGES	CAN (20)	-6.4 ^a	-0.8 ^a	-3.6 ^A
	FYM (63)	1.7 ^c	0.2 ^a	1.0 ^B
	CAN + FYM (83)	-0.9 ^b	1.6 ^b	0.3 ^B
Mean		-1.8^a	0.3^a	-0.7^A
GRAND MEAN		1.4	1.6	1.5
SED				
Season	0.401ns			
Ridging	<.001***			
Fertilizer	<.001***			
Season*Ridging	<.001***			
Season*Fertilizer	<.001***			
Ridging*Fertilizer	<.001***			
Season*Ridging*Fertilizer	<.001***			
% cv	10.7			

SED- standard error of differences of means, **, ***significant at $p \leq 0.05$ and 0.001 , **ns**- not significant. Means across rows or columns followed by different letters are not significantly different at $P \leq 0.05$. Small letters (a,b,c) are for individual treatments while capital letters (A,B,C) are for the interaction effect.

CHAPTER FIVE

DISCUSSION

5.1 Soil characterization

Soil pH at the study site was 5.60, implying that it was appropriate for production of maize since it thrives best at soil pH ranging between 5.5 to 8.0 (Jaetzold *et al.*, 2007). The soils were deficient in Nitrogen (N) and phosphorus (P) levels and had low organic matter content. Kwena *et al.*, (2017) had reported similar outcome. This can be accredited to continuous tilling of land without satisfactory replenishment of nutrients and organic matter. To address the issue of low organic matter content, it is vital to apply adequate quantities of good quality manure. The low nutrient levels could also be due to loss of nutrients through erosion (Appendix VI) and runoff.

5.2 Soil moisture contents as affected by tied ridging and fertilizer application

Soil moisture depends on numerous environmental factors comprising of rainfall, temperature variation, soil properties, and moisture storage capacity (Karuma *et al.*, 2012). Moisture content of the soil varied across tied and untied ridges with the latter having higher content than the former. This was probably because there was more foliage in the presence of the initial soil moisture, meaning more water was lost through evapotranspiration. However, on the positive dimension, this brought about higher yields. According to Han *et al.*, (2025), warming coupled with enhanced drainage and aeration both in poorly and moderately well-drained soils permits ridges to dry out quicker than flat soils do. Karuma *et al.*, (2014), also realized that tied ridges in LR 2013 held lower soil moisture than conventional tillage. Equally, Ndung'u *et al.*, (2023)

noted that tied ridging without addition of organic inputs conserved scanty moisture owing to very little rain water stored in the basin.

Soil moisture also changed during certain maize growth stages. In SR 2013, the highest soil moisture occurred in the 13th WAP, while in SR 2014, it peaked in the 14th week, both aligning with somehow heavy rainfall events. This implies that rainfall timing and distribution strongly influences soil moisture and crop water uptake.

During SR 2014, plots with FYM held more moisture than control plots, because manure bound the soil particles together, improving its structure, thus enhancing soil moisture retention capacity. This is congruent to Miriti *et al.*, (2012) results who found that manure increased available water by about 20% compared to plots without manure. Ndung'u *et al.*, (2023) also stated that treatments containing organic inputs performed best in holding soil water relative to those without, attributing to improved soil physical conditions which increased the soil water-holding capacity. These concurred with Brar *et al.*, (2015), results who observed that manure conserved soil moisture, improved soil physico - chemical properties, and reduced soil temperature, which minimized evaporation. Correspondingly, Jiang *et al.*, (2024) also observed that soil organic matter and moisture contents were enhanced by applying manure.

5.3. Water use efficiency ($\text{kg ha}^{-1} \text{mm}^{-1}$) as influenced by tied ridging and fertilizer application

Soil water use efficiency is an indispensable crop index used to assess how soil water is used efficiently for total biomass and grain yield. When it came to WUE, tied ridges

outdid untied ridges. This could be because the low moisture in ridges encouraged soil aeration and upheld root vitality, thus minimising damage due to waterlogging (Han *et al.*, 2025). According to Wainaina, (2023). Tied ridges reduces water loss from erosion and evaporation, retaining more moisture in the soil for crop utility. Oduor *et al.*, (2023) also noted that tied ridges improved WUE by 50–65% compared to conventional tillage.

Fertility also had an impact on WUE as plots treated with FYM had higher WUE than those without. This could be because manure improved soil structure and enhanced hydrological properties, facilitating effective use of water by crops (Oduor *et al.*, 2023). Moreover, fertilizers encourage stronger root systems, allowing plants to access soil water at greater depths during dry periods (Drechsel *et al.*, 2015). Better nourishment also boosts crop growth and canopy cover which in turn reduces evaporation from the soil surface, further improving WUE (Wondimu *et al.*, 2024). Research has revealed that providing crops with sufficient nutrients greatly improves how efficiently they utilize water. For example, Kathuli and Itabari (2014), found that applying fertilizers and manures boost WUE. Hu *et al.*, (2023) even reported that nitrogen fertilizer alone increased WUE by 20%, regardless of how much rain fell in a season. Good results were seen when FYM was used on tied ridges. Kathuli and Itabari, (2014) confirmed that tied ridging in combination with fertilizer improved WUE significantly from 0.29 to 3.75 kg ha⁻¹ mm⁻¹.

5.4 Maize grain yield (t ha⁻¹) in response to tied ridging and fertilizer application

Water and nutrient availability closely interact to influence the growth and yield of crops. The variation in yields across seasons as observed could be accredited to the

varying distribution and quantity of rainfall. This implies that rainfall amount and distribution are fundamental to crop development, as lack of it may subject crops to moisture stress during a critical period of its growth (Oduor *et al.*, 2020). SR 2013 season had 24% higher rainfall amount than SR 2014 thus explaining the 53% yield variation between the two seasons. Rainfall shortages or mid-season dry spells explain the generally low yields despite fertilizer application and water conservation measures.

Crops planted on tied ridges produced about 18% more grain than those on untied ridges. This suggests that the tied ridging also had a strong impact on boosting maize yields. Comparable outcome was reported in Machakos County by Karuma *et al.*, (2014), revealing that tied ridges enabled maize to grow in low rainfall years when flat planted crops performed below par. Adeboye *et al.*, (2017) also found that tied ridges furrow- rain- water harvesting augmented yield of maize by 14.0% - 41.8% compared to flat planting. They accredited this to the higher amount of rain water that infiltrates the soil under tied ridges, which in turn improves the crop response to both fertilizer and rainfall. A study by Ndung'u *et al.*, (2023) reported similar outcomes where tied ridging produced the utmost yield increase of maize grain compared to flat planting. Likewise, Wainaina, (2023) documented yield increase under tied ridging compared to flat planting.

Fertilizer application had an effect on maize grain yield in both tied and untied ridged plots. Farm yard manure (FYM) plots gave the greatest positive response of crop yields to fertilizer application. This could be due to improved capacity of the soil to hold water, as enabled by manure. FYM conserved more soil water which most likely improved plant nutrient availability and crop's uptake. Furthermore, addition of FYM enhances

soil microbial activities leading to release of nutrients after decomposition which in turn increases crop yields (Belay *et al.*, 2023) . Regardless of poor rainfall during LR and SR 2008 seasons, Miriti *et al.*, 2012), still realized significant manure effects in the yield. He reported 37% increase in maize grain yield in manure plots (1.22 Mg ha^{-1}) compared to treatments without manure (0.89 Mg ha^{-1}). Related findings were reported by Innocent *et al.*, (2014) who observed increased yields due to use of farm yard manure.

Generally, FYM plots under tied ridging gave the topmost mean yield. This might be because when tied ridges was coupled with FYM application, there was an improved soil physical conditions together with improved soil moisture retention hence higher crop yields. The effect of fertilizer on yield depends on available water and there is often a beneficial interaction between these two components (Drechsel *et al.*, 2015). This is congruent to Kathuli & Itabari, (2014), findings that tied ridging with fertilizer application can increase crop yields by 100–359% Mak-Mensah *et al.*, (2021) also found that millet grain yield increased by 20% to 40% in tied-ridge-furrow treatments with fertilizer application compared to tied-ridge-furrow without mulching or fertilizer treatment.

5.5 Nitrogen use efficiency as influenced by tied ridging and fertilizer application

Nitrogen Use Efficiency (NUE) is a critically significant concept for assessing crop production systems and is greatly influenced not only by fertilizer management but also soil and plant-water relationships (Drechsel *et al.*, 2015). In order to assess the

efficiency of maize in utilizing nitrogen fertilizer for grain production, NUE was determined.

Tied ridges had higher NUE than untied ridges owing to absorption of nutrients as impacted by soil moisture content. Apart from supporting growth, a steady supply of moisture also ensures efficient absorption of nutrients by plants (Drechsel *et al.*, 2015). However, with sufficient water, nutrients supplied to the field becomes more available and can be taken up more effectively by crops, improving fertilizer use efficiency (Cao *et al.*, 2023). Most essential plant elements exist in their elemental forms in the soil, yet plants normally absorb them as ions. Mineralization, a process of transforming the nutrients from elemental to ionic forms, heavily depends on soil moisture (Drechsel *et al.*, 2015). This further explains why treatments having more soil moisture tended to produce greater yields.

In contrast, nutrient use efficiency (NUE) under untied ridges was lower, probably because in dry or moisture-deficient soils, nutrients remain in their elemental states and are not easily absorbed by plants, leading to immobilization (Qin *et al.*, 2022). The cations in such soils are more tightly bound to soil particles, making them less accessible. Moreover, the breakdown of organic matter slows down when moisture is lacking, further limiting nutrient release (Drechsel *et al.*, 2015). As a result, during dry periods, plants often show nutrient concentration below normal levels in their tissues, which helps explain the reduced yields observed in untied ridge plots (Qin *et al.*, 2022)

Plots with FYM recorded the highest NUE. This could be because adding organic matter to soil improves its nutrient obtainability and uptake by plants.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

This study evaluated the influence of integrated soil fertility and water management practices on maize grain yield, water use efficiency and nitrogen use efficiency in a semi-arid region of Eastern Kenya (Machakos County). The study found that tied-ridging when combined with FYM application increased maize grain yield, WUE and NUE by 18, 30 and 125%, respectively.

6.2. Recommendation

I recommend the Ministry of Agriculture to encourage farmers in the area to adopt water management practices, in this case, tied-ridges and soil fertility management, farm yard manure to be specific, in order to improve maize production in arid regions. Moreover, I propose that further studies to evaluate;

- i. Influence of integrated soil fertility and water management practices on maize grain yield, WUE and NUE using other cultivars of maize adapted to arid regions and especially the local ones.
- ii. Influence of integrated soil fertility and water management practices on maize grain yield, WUE and NUE using more soil moisture maintenance measures such as terraces

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APPENDICES

Appendix I: Tied Ridges at the Experimental Site (Source, Author, 2014)



Appendix II: Application of FYM at the site and mixing with soil



Appendix III: Marking out the effective harvesting area prior to the harvesting exercise

(Source: Author, 2014)



Appendix IV: Interpretation of soil and FYM data

1. Grading levels of soil acidity at KALRO- Kabete (Kanyanjua *et al.*, 2002)

pH ranges	Degree of acidity
<4.5	extremely acidic
4.5 - 5.2	strongly acidic
5.3 - 5.9	moderately acidic
6.0 - 6.5	slightly acidic
6.5 -7.0	near neutral

2. Carbon and organic matter (Source: Thomas *et al.*, 1997)

% Carbon	% Organic matter⁺⁺⁺	Rating
<1.0	<1.7	Low
1.0-2.0	1.7-3.4	Moderate
2.0-4.0	3.4-6.9	Adequate
>4.0	>6.9	High

+++% soil organic matter has been calculated by multiplying &C by the 1.72 factor

3. Total Nitrogen (Source: Thomas *et al.*, 1997)

% N	Rating
<0.2	Low
0.2-0.5	Moderate
>0.5	High

4. Available phosphorus (Mehlich)

Mg Pkg⁻¹	Rating
<20	Low
20 - 80	Moderate
>80	High

5. Exchangeable cations (Source: Thomas *et al.*, 1997)

Element	Low	Moderate	High
Potassium (K)	<0.2	0.2 - 1.5	>1.5
Calcium (Ca)	<0.2	0.2 - 1.5	>1.5
Magnesium (Mg)	<1.0	1 - 3.	>3

APPENDIX V: Analysis of Variance Tables**1) ANOVA TABLE FOR WUE**

Source of variation	Degree of freedom	Means of squares	F probability
Season	1	0.0523	0.608 ns
Ridging	1	12.0736	<.001 ***
Fertilizer source	3	5.4565	<.001 ***
Season*Ridging	1	1.4811	0.009 **
Season*Fertilizer source	3	1.5336	<.001***
Ridging*Fertilizer source	3	4.1853	<.001***
Season*Ridging*Fertilizer source	3	0.9333	0.006 **

2) ANOVA TABLE FOR YIELD

Source of variation	d.f.	m.s.	F pr.
Season	1	72727	0.002 **
Ridging	1	56053	0.005 **
Fertilizer source	3	32075	0.005 **
Season* Ridging	1	2	0.986 ns
Season*Fertilizer source	3	6242	0.417 ns
Ridging*Fertilizer source	3	27917	0.009 ***
Season*Ridging*Fertilizer source	3	6034	0.432 ns


3) ANOVA TABLE FOR NUE

Source of variation	Degree of freedom	Mean of squares	F probability
Season	1	0.3408	0.401 ns
Ridging	1	181.842	<.001 ***
Fertilizer source	2	21.8673	<.001 ***
Season*Ridging	1	34.9578	<.001 ***
Season*Fertilizer source	2	13.4876	<.001 ***
Ridging*Fertilizer source	2	39.3436	<.001 ***
Season*Ridging*Fertilizer source	2	10.0261	<.001 ***


Appendix VI: Effects of soil erosion on maize at different growth stages (Source: Author, 2014)



Appendix VII: Similarity report



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