Effect Of Zai Pits, Mulch and Manure on the Growth and Yield of Green Grams in Maragua Sub County

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A Research Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science in Agricultural and Rural Development (dry land farming), Kenya Methodist University

September 2025

DECLARATION

I declare that this is my original work that have never been submitted in any other institution for marking.

Sign: ……………………………… Date: …………………………..

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AGR-3-0068-1/2022

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DEDICATION

This work is dedicated to my family especially my grandmother, my spouse, and my daughters whose unwavering love and support have been a constant source of strength and inspiration throughout this academic journey.

ACKNOWLEDGEMENT

Sincere gratitude is extended to my supervisors, Dr. David Mushimiyimana (PhD) and Dr. Mworia Mugambi (PhD), for their invaluable guidance and support throughout this research. Their expertise and constructive feedback greatly contributed to the successful completion of this thesis. Appreciation is also due to colleagues, friends, and fellow students for their encouragement and collaboration during the study. Special thanks go to the staff of the Department of Agriculture at Kenya Methodist University for their continuous support. Deep gratitude is owed to my family for their love, understanding, and patience during the course of my studies. Lastly, heartfelt appreciation is extended to all research participants for their time and input, without which this work would not have been possible.

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ABSTRACT

Green grams are crucial for human nutrition and environmental sustainability. Abundant in protein, fiber, and other nutrients, they enhance global food security, especially in areas with restricted protein consumption. Their cultivation boosts soil health and fertility, diminishes reliance on synthetic fertilizers via nitrogen fixation, and bolsters agricultural sustainability. Green grams are essential for human health, environmental sustainability, and agricultural success. However, erratic rainfall and temperature patterns significantly affect agricultural productivity, especially in arid areas such as Maragua Subcounty, Kenya. The research was directed by the subsequent objectives: (i) Evaluation of the impact of zai pits, mulch, and manure on the growth parameters and yield of green gram production, (ii) Investigation of the impacts of mulch and manure on the yield of green gram production. The data gathered throughout the experimental phase encompassed growth metrics of green gram, including leaf count, girth, height, and yield. The field experiments employed a randomized complete block design (RCBD) to guarantee the reliability and robustness of the results. The study employed an experiment to assess the impact of various treatments on the growth and yield of green gram production. Two replicates, each with its corresponding experimental units. Each replication comprises eight primary plots. The total number of plots per experimental site will be 16, yielding 96 sub-plots as each plot is divided into two sub-plots to accommodate the 8 types; this configuration will constitute a split-plot design. Each plot spans 2 meters by 2 meters, and each sub-plot has treatments implemented within an area of 60 cm by 60 cm, with a spacing of 80 cm by 20 cm between treatments. The analysis and data management of the collected data were performed using SPSS. An ANOVA test was performed to statistically evaluate the significance of the observed variations in plant height among the various treatments. The results indicated that the treatments had a statistically significant impact on plant height ($p < 0.001$), but site and block effects were not significant, demonstrating uniformity in the treatment response across the experimental conditions. Yield statistics corroborated these findings, indicating incremental gains from traditional farming to the integrated zai pit, manure, and mulch treatments. The traditional treatment yielded the least, whereas zai pit-based treatments, particularly when supplemented with manure and mulch, yielded the most. Duncan's multiple range test identified seven unique subsets, demonstrating incremental and statistically significant yield enhancements with each additional treatment component. The research concludes that the incorporation of zai pits with organic soil amendments such as manure and mulch markedly enhances green gram development and yield in semi-arid conditions. The integration of these strategies improves soil moisture retention, nutrient accessibility, and general plant health, leading to enhanced vegetative growth and optimal yields. Smallholder farmers in semi-arid regions should implement integrated zai pit technology alongside organic inputs, such as manure and mulch, to optimize green gram productivity and enhance resilience to moisture stress.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Globally, crop productivity has been hampered by a lack of nutrients and inadequate water availability (Hengsdijk & Langeveld, 2019). In addition to insufficient nutrients, another important factor causing crop yield to decline or stagnate is the restricted amount of soil moisture (Rockström et al., 2017). Furthermore, Grafton et al. (2015) pointed out that the regular occurrence of prolonged dry spells and water shortages, which are common in rain-dependent farming in Africa as reported by Rockström et al. (2017) poses a serious threat to the country's projected future food needs by 2050. Similarly, the Intergovernmental Panel on Climate Change (IPCC) study from 2007 unequivocally asserts that climate change had a significant impact on agricultural productivity. According to the available information, rain-fed agriculture in Africa is particularly vulnerable to changes in the weather.

According to Gichangi et al. (2017), crop cultivation in Kenya's semi-arid regions is significantly hampered by low soil fertility and limited moisture availability. Kenya has had severe droughts in 1971–73, 1983–84, 1991–92, and most recently, 2004–2006, which have left 2.5 million people without enough food. Additionally, according to Rarieya and Fortun (2018), the droughts that occurred between 2008 and 2010 caused a food crisis and impacted 10 million people. Additionally, according to Grafton et al. (2015), the present worldwide yearly growth rates for important cereal crops range from 0.9% to 1.6%, and they have decreased over the past 20 years.

The discrepancy between farmers' actual and potential crop yields highlights the significance of introducing innovative agricultural practices in sub-Saharan Africa.

According to Rockström et al. (2017), the observation suggests that integrating nutrient management and soil water conservation strategies is necessary to successfully address the issue of poor yields in rainfed farming systems in developing nations. As highlighted by Winterbottom et al. (2017), synergistic effects can be realized by combining water collection technologies with better soil fertility management techniques. This will increase water efficiency and yields on smallholder farms. According to Dile et al. (2015), the implementation of suitable methods for soil and water management, like the zai pit proposed by Evett and Tolk (2016) can improve rainfall utilization and lessen dry spells during the growing season.

The zai pit technique has demonstrated benefits in raising rainfall capture, reducing runoff and evaporation, and improving agricultural productivity, claim Evett and Tolk (2016). According to Campbell et al. (2014), farmed lands usually encounter a number of challenges, including crusting, hardpan layer formation, compacted soils, restricted root development, inadequate aeration, and decreased plant permeability. According to Kaboré and Reij (2016), the excavation of pits aids in water infiltration, and the building of earthen bunds downslope of the pits permits the gathering of runoff water. But according to Burpee et al. (2015), combining organic and inorganic elements with zai pits increases their efficacy even more. Applying such materials improves crop uptake of nutrients from the soil's existing stores while also increasing the availability of soil nutrients.

In Machakos County, Kenya, during the 1995 short rainy season, the installation of zai pits without fertilizers resulted in a significant ($p = 0.05$) tenfold increase in sorghum grain yields in comparison to plots without zai pits and without fertilizers, according to Kathuli and Itabari (2015). According to Campbell et al. (2014), zai systems have a favorable impact on crop performance in semiarid environments because they increase soil water availability and promote nutrient release and decomposition, which raise soil fertility. Therefore, the main goal of this study is to assess how well the zai pit method works in semi-arid and dry regions to retain moisture and restore soil fertility. In particular, the study will focus on examining how zai pits affect the production of green grams, which was used as the experimental crop.

Kenya is not the only country in sub-Saharan Africa, where agriculture is heavily reliant on rainfall, to face the problems of water scarcity and low soil fertility. These problems have been made worse by climate change, which has resulted in more frequent droughts and unpredictable rainfall patterns. The necessity for adaptable agricultural methods that might assist farmers in adapting to the changing environment has been emphasized by this variability. In order to guarantee food security and enhance the standard of living for smallholder farmers in these areas, technological interventions such as methods for gathering water and managing soil fertility have become crucial. There has never been a more pressing need for climate change-resilient farming systems, and implementing such systems may be essential to reducing the negative effects of climate variability on crop yields.

Furthermore, in many agricultural locations, soil deterioration continues to be a significant concern. The soil's ability to support healthy crop growth has been further diminished by the depletion of vital nutrients brought on by the overuse of chemical fertilizers and poor soil management techniques. In semi-arid areas, where there is little vegetation cover and rainfall, soil erosion and nutrient loss are increased, making the situation especially grave. Therefore, the effects of soil degradation could be considerably mitigated by including soil conservation practices such as zai pits, which are intended to enhance soil fertility and water retention. When paired with organic inputs that can replace the soil's nutrient reserves, the zai pit method provides a sustainable and affordable way to assist restore the productivity of degraded soils.

Finally, although the zai pit method has demonstrated its effectiveness in improving crop yields in various parts of Africa, its adoption is still limited in certain areas due to various socio-economic and cultural barriers. Farmers often face challenges in accessing the necessary resources to implement and maintain such techniques, including labor, tools, and technical knowledge. Additionally, the perceived complexity and unfamiliarity of new farming practices may deter farmers from adopting them. Overcoming these barriers requires tailored extension services that can provide farmers with the knowledge and support they need to successfully implement zai pits and other water conservation technologies. Understanding the factors that influence the adoption of these techniques is crucial for designing effective interventions that promote sustainable farming practices in semi-arid and arid regions.

1.2 Statement of the Problem

Inadequate soil fertility and water scarcity presented considerable obstacles to rainfed agriculture in the low midland regions of Maragua Sub-county and Mbeere South Sub-County. At that time, there was scant information or published study concerning the effects of integrating zai pits with mulch or manure on green gram yields. While numerous research in Africa have yielded significant insights into the effects of zai pits on cereal crop performance, it was crucial to evaluate their use with alternative soil fertility management amendments.

This study sought to evaluate the impact of employing zai pits with mulch and manure on the production of drought-resistant green grams. The research aimed to examine how the integration of zai pits with mulch and manure improved the crop yield of green grams in semi-arid areas.

The use of integrated soil fertility management strategies, which blended zai pits with organic additions like mulch and manure, was regarded as a potentially sustainable approach to enhancing soil quality and crop productivity in the region. Although individual technologies such as zai pits have demonstrated potential in water capture and moisture retention, the combined impacts of integrating these methods with organic inputs have yet to be thoroughly investigated. The use of mulch and manure not only augmented organic matter in the soil but also enhanced soil structure, facilitated nutrient cycling, and mitigated soil erosion all essential elements for improving crop yields in arid regions. The study offered essential empirical information regarding the synergistic benefits of these activities, enhancing the comprehension of how integrated approaches might tackle the concurrent issues of water scarcity and soil fertility in Maragua Sub County and Mbeere South Sub County.

1.3 Objectives of the Study

1.3.1 General Objective

The primary aim of the research was to explore the efficiency of the Zai Pit method combined with organic manure or mulch in retaining moisture and revitalizing soil fertility thus improving growth and yields of green grams in semi-arid areas

1.3.2 Specific Objectives

The following specific objectives guided the study:

i. To assess the effects of zai pits on the growth parameters on and yield of green grams production.

ii. To find out the effects of mulch and manure on yield of green grams production.

iii. To evaluate the economic viability of using zai pits, mulch, and manure in green gram production.

1.4 Hypotheses of the Study

i. There is a significant effect of zai pits on the growth parameters on the yield of green grams

ii. There is a significant difference in the effects of mulch and manure on the green grams production.

iii. There is a significant difference in the economic viability of using zai pits, mulch, and manure in green gram production compared to conventional farming practices.

1.5 Significance of the Study

The findings of this research provided essential insights to farmers and agricultural extension agents, aiding them in the design and implementation of zai pits. The identification of critical characteristics that facilitated the successful implementation of water harvesting structures was employed to enhance agricultural output. The findings offered essential insights for extension service providers in the development, coordination, and evaluation of effective agricultural policies, initiatives, and projects at local, regional, and national levels. The emphasis was on assisting small-scale farmers in sub-humid and semi-arid areas of Sub-Saharan Africa.

Furthermore, the study's findings offered smallholder farmers significant advice regarding appropriate technology for augmenting soil fertility, adopting water harvesting techniques, increasing yields, and promoting economic efficiency. This strategic initiative sought to tackle issues pertaining to food security and poverty reduction.

The study's findings also improved the resilience of smallholder farmers against climate change by offering flexible, cost-effective approaches. In areas characterized by water scarcity and soil fertility issues, the implementation of water collecting and fertility-enhancing techniques like zai pits enabled farmers to more effectively address environmental constraints. The study's significance also resides in its capacity to guide future research in sustainable agriculture, allowing policymakers to formulate interventions that promote climate-resilient farming systems. The study promoted wider implementation of validated methodologies by publicizing the results to local communities and stakeholders, hence enhancing food security and rural livelihoods.

1.6 Justification of the Study

This study was significantly pertinent to the agricultural practices in Maragua Subcounty and Mbeere South Subcounty. Agriculture in these regions depended significantly on rainfed systems, rendering it susceptible to erratic rainfall patterns and recurrent droughts. The study examined the impact of zai pits in conjunction with organic amendments such as mulch and manure, thereby addressing a significant knowledge gap in sustainable farming techniques. Smallholder farmers, confronted with issues like water scarcity and soil degradation, directly profited from the findings, allowing them to use effective measures that enhanced water retention, soil fertility, and crop yields, so improving their livelihoods.

Climate change has resulted in increasingly irregular weather patterns, intensifying the difficulties of agricultural production in Sub-Saharan Africa. This study was opportune, as it provided viable remedies for the detrimental impacts of climate change on food security. The research analysed water gathering strategies such as zai pits, which aim to store moisture and enhance soil fertility, offering vital insights into how agricultural communities might adapt to shifting climatic conditions. The findings resulted in the creation of more robust agricultural systems that can maintain productivity despite increasingly erratic rainfall, rendering the study essential for long-term agricultural sustainability.

The study's results could extend beyond the confines of Maragua Sub County and Mbeere South Sub County. The study examined the synergistic application of zai pits and organic inputs, proposing a method suitable for diverse regions of Sub-Saharan Africa. The prevalent issues of soil infertility and water shortage have influenced agricultural policy and practices in the region, benefiting a broader demographic of small-scale farmers. This strategy, if successful, was anticipated to be duplicated in other semi-arid locations, so aiding in the resolution of pervasive food security challenges and fostering rural development on a broader scale.

The study's conclusions significantly influenced agricultural policies and extension activities in Kenya and elsewhere. The research identified effective water conservation measures and soil fertility management approaches, offering evidence-based suggestions that informed policymakers and agricultural extension agents in developing targeted interventions. Moreover, the study's focus on smallholder farmers in sub-humid and semi-arid regions guaranteed that its conclusions were pertinent to the populations most in need of assistance. The research facilitated the creation of more extensive training programs for farmers, equipping them with the information and skills necessary to enhance productivity and resilience via novel agricultural methods.

1.7 Definition of Terms

Organic Matter denotes the decomposed remnants or waste products originating from flora, fauna, or other biological entities. It comprises carbon-based chemicals and is abundant in nutrients including nitrogen, phosphorus, and potassium.

Soil Fertility It relates to the soil's ability to provide essential nutrients and conditions necessary for plant growth and development.

Water Retention Capacity denotes the soil's capability to hold and store water for plant utilization. It denotes the maximum volume of water that soil can retain and supply to plant roots prior to surplus water draining away or becoming inaccessible for plant absorption.

Zai Pits are small planting pits or holes dug in the soil as a soil and water conservation technique used in arid and semi-arid regions. The pits are typically spaced at regular intervals and are designed to capture and retain water during rainfall events. They are commonly used to improve soil fertility, moisture retention, and overall crop productivity in areas with limited rainfall and degraded soils.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In arid locations with erratic rainfall patterns, Kenyan farmers predominantly cultivate robust crops such as millet and sorghum. These crops are produced alongside legumes such as green gram, beans, cowpea, and pigeon pea, establishing a symbiotic relationship that provides reciprocal advantages. A notable constraint on land productivity in these places is inadequate soil moisture, as indicated by Kathuli and Itabari (2015). Prior investigations in this domain have consistently shown that integrating rainwater harvesting methods with soil fertility enhancements significantly enhances crop yields, as evidenced by studies by Kathuli and Itabari (2015) and Gichangi et al. (2017).

2.1.1 Green Grams Production

Green grams (Vigna radiata), commonly referred to as mung beans, are highly suited to semi-arid environments and thrive at elevations between sea level to 1600 meters above sea level. These regions are defined by temperate climatic conditions, which are crucial for the effective growth and development of the crop. Green grams thrive on well-drained sandy loam and clayey soils with a pH between 5.5 and 7.5, facilitating nutrient availability and root development (Mucheru-Muna et al., 2010). Their drought-resistant characteristics render them an advantageous option for smallholder farmers in arid and semi-arid lands (ASALs), where annual precipitation varies from 350 mm to 700 mm. increased rainfall beyond this threshold can result in increased vegetative growth, compromising reproductive structures and ultimately impacting pod formation and production (MoALF, 2016).

Effective site preparation is essential for attaining optimal plant density and robust crop establishment. Ploughing during arid periods is strongly advised as it improves soil aeration, inhibits weed proliferation, and exposes soil-dwelling pests to dehydration and predation, hence aiding in pest control (ICRISAT, 2015). The disintegration of soil clods to attain a fine to medium tilth promotes uniform germination and seedling establishment, essential for assuring a consistent crop stand.

Organic matter significantly enhances soil fertility, water retention, and microbial activity. It is advisable to spread well-decomposed farmyard manure at a rate of 200 wheelbarrows per acre prior to planting, enhancing soil structure and nutrient availability (Njeru et al., 2014). Green grams are seeded at a seed rate of 4–6 kilos per acre for seeding. Optimal spacing, generally 45 centimetres between rows and 15 centimetres between plants, guarantees sufficient light interception, aeration, and nutrient absorption. Seeds are to be sown at a depth of 3–5 centimetres to prevent shallow roots or susceptibility to desiccation (MoALF, 2016).

Efficient weed management is essential, especially during the initial weeks post-emergence, when weeds vie with the crop for moisture, nutrients, and light, and may act as alternate habitats for pests and diseases. Weed management should preferably occur two weeks post-emergence and prior to flowering to mitigate adverse interactions (KARI, 2012). Application of foliar feeds prior to flowering and throughout the fruiting phase has been shown to augment vegetative vigor and promote pod development, resulting in increased yields (Mucheru-Muna et al., 2010).

The harvesting of green grams should occur at physiological maturity, indicated by dry, shrivelled pods and hardened seeds. At this juncture, the plant has finalized its lifetime and attained optimal seed quality. Harvesting is generally conducted manually via hand-picking, frequently on a weekly schedule because to the non-uniform maturation of the pods. Farmers may opt to harvest individual pods or uproot entire plants for sun-drying over a period of two days prior to threshing and cleaning. This stage, although labour-intensive, is essential for preserving seed quality and market value. Harvesting is the most labour-intensive and expensive phase in green gram production, frequently constituting a substantial amount of the overall production cost (MoALF, 2016).

Pest and disease management is a crucial component of green gram cultivation, as infestations can markedly diminish output and grain quality. Insect pests that commonly afflict green grams include aphids, whiteflies, pod borers, and thrips, which not only harm the plant but also serve as carriers for viral illnesses like Yellow Mosaic Virus (YMV) (KARI, 2012). Recommended Integrated Pest Management (IPM) tactics encompass the utilization of certified seeds, crop rotation with non-leguminous species, prompt weeding, and the application of biological control agents such as parasitic wasps. In instances of significant infestations, the prudent application of approved pesticides may be utilized, ensuring adherence to appropriate pre-harvest intervals to prevent chemical residues on harvested goods (MoALF, 2016). Moreover, fungal infections like powdery mildew and Cercospora leaf spot can impair plant leaves and diminish photosynthetic efficiency. These diseases flourish in warm, humid environments, and their management may need the application of fungicides, the elimination of contaminated plant debris, and the utilization of resistant kinds wherever accessible (ICRISAT, 2015). Maintaining optimal field cleanliness and conducting regular assessments of crop health are critical measures for reducing crop losses attributable to pests and diseases.

Recently, the development of enhanced green gram cultivars has substantially advanced productivity in semi-arid locations. These enhanced cultivars have been engineered to endure drought, resist pests and diseases, and provide superior yields relative to conventional landraces. These types frequently exhibit superior genetic potential for uniform maturity and improved seed quality, rendering them more appropriate for local consumption and export markets (Mucheru-Muna et al., 2010). The use of these enhanced cultivars, along with effective agronomic practices, has resulted in heightened productivity in regions where green gram agriculture was hitherto restricted by climate limitations and subpar soil conditions. Moreover, research and development initiatives aimed at varietal enhancement, such as breeding for disease resistance and reduced growth durations, are essential to satisfy the increasing demand for green grams, particularly in light of climate change and altering precipitation patterns.

The marketing and post-harvest management of green grams significantly influence the success of green gram cultivation in ASALs. Post-harvest handling practices, including cleaning, grading, and packaging, are crucial for preserving seed quality and securing elevated market values. Green grams are frequently marketed in both domestic and global markets, where they are sought after for their nutritional benefits, particularly their elevated protein and fibre content. The formation of structured farmer organizations and cooperatives can significantly enhance farmers' negotiating strength and access to superior market prices, in addition to facilitating chances for bulk sales. Moreover, investments in storage facilities that inhibit moisture penetration and insect infestation can reduce post-harvest losses and prolong the shelf life of grains, enabling farmers to market their produce year-round. Effective market access and post-harvest management can enhance the profitability of green gram growing for smallholder farmers in Kenya's semi-arid regions (MoALF, 2016; ICRISAT, 2015).

2.1.2 Use of Zai Pit

The zai pit technique is a traditional water harvesting and soil fertility enhancement strategy that has been adapted and improved in semi-arid regions of Sub-Saharan Africa, including Kenya. It plays a vital role in ensuring food security by improving crop performance in areas that experience unreliable and erratic rainfall. This method supports three core conservation goals: soil fertility maintenance, water retention, and erosion control (Reij et al., 2009). Zai pits function by concentrating water and nutrients around plant roots, thus creating microenvironments that enable crops to survive and thrive even under harsh conditions.

In Kenya, one of the most effective adaptations of this technology is the "five by nine" zai pit system. This system involves digging pits that measure approximately 0.6 meters in length, 0.6 meters in width, and 0.6 meters in depth a size slightly larger than conventional zai pits used in other parts of Africa (Kathuli & Itabari, 2015). The term "five by nine" stems from the planting arrangement within the pits, where five maize seeds are planted in arid areas and nine seeds in more humid environments. This configuration maximizes seed utilization while ensuring adequate root spacing for optimal nutrient and moisture uptake (Mati, 2005).

To improve the pits' effectiveness in capturing and retaining runoff water, they are typically spaced 0.6 to 0.8 meters apart and aligned in staggered (alternating) rows across a sloping field. This layout not only minimizes surface runoff but also enhances water infiltration and reduces the loss of topsoil through erosion (Zongo et al., 2015). Each pit is enriched with organic inputs such as farmyard manure, compost, or crop residues before planting. These amendments improve soil structure, enhance microbial activity, and increase nutrient availability to plants (Kaboré & Reij, 2004). In many cases, farmers allow the organic matter to decompose in the pit for several weeks before sowing, which improves the efficiency of nutrient uptake during the critical early stages of plant development.

Furthermore, zai pits can be reused for two to three cropping seasons with minimal re-digging, which helps conserve labor and reduces soil disturbance over time (Mati, 2005). Their use has also been linked to increased resilience of smallholder farming systems to climate change, as they provide a low-cost and effective method for rehabilitating degraded lands. Research conducted in Kenya and the Sahel region has demonstrated significant yield improvements in cereals like maize and millet through the use of zai pits, especially in fields that were previously unproductive due to land degradation or poor water retention (Reij et al., 2009; FAO, 2016).

While the zai pit technique is traditionally associated with smallholder farming in arid and semi-arid regions of Sub-Saharan Africa, its principles are increasingly being explored in developed nations, especially in areas facing the challenges of climate change-induced drought and soil degradation. For instance, parts of the southwestern United States, such as Arizona and New Mexico, have demonstrated interest in adapting zai-like micro-catchment systems for dry land farming and soil restoration. These areas suffer from water scarcity and declining soil health, making them ideal candidates for low-cost, sustainable technologies like zai pits (Mills et al., 2013). Researchers and practitioners in the U.S. have modified the original zai pit design by incorporating modern tools such as soil moisture sensors and composting techniques to improve water use efficiency and crop yield (Sustainable Agriculture Research & Education [SARE], 2018). Such adaptations align well with the goals of regenerative agriculture, which focuses on building soil organic matter and improving the water-holding capacity of soils an urgent need even in technologically advanced farming systems.

Moreover, the integration of zai pits with other sustainable agricultural practices, such as crop rotation and agroforestry, further enhances their benefits in promoting food security and environmental sustainability. By combining zai pits with diversified cropping systems, farmers can improve soil nutrient cycling and reduce pest and disease pressures, which are common challenges in monoculture farming. Additionally, the use of cover crops in rotation with main crops such as maize or millet can provide organic matter to the soil, further enriching its fertility and structure. This holistic approach is gaining popularity among farmers in Kenya and other parts of Sub-Saharan Africa, who are increasingly realizing the synergistic effects of combining different traditional and modern farming methods for increased resilience to climate variability (Kathuli & Itabari, 2015).

On a broader scale, the adoption of zai pits as a sustainable land management practice has received attention from development organizations and governments. This technique is increasingly seen as a key strategy for addressing land degradation, improving food security, and mitigating the effects of climate change in rural areas. International institutions such as the Food and Agriculture Organization (FAO) and the International Fund for Agricultural Development (IFAD) have provided funding and technical support to scale up zai pit practices in regions vulnerable to droughts and desertification. These initiatives aim to empower smallholder farmers by providing them with the tools and knowledge necessary to implement zai pits effectively and sustainably. As more farmers adopt this technique, it has the potential to contribute significantly to achieving global goals related to sustainable agriculture, poverty reduction, and climate resilience (FAO, 2016; Reij et al., 2009).

2.2 Soil Fertility Amendment Options

Soil fertility is a cornerstone of agricultural productivity, particularly in arid and semi-arid regions (ASALs) where the degradation of land is a major constraint to food security. Smallholder farmers operating under these harsh environmental conditions often encounter depleted soils with low organic matter, poor structure, and minimal nutrient availability. To reverse this trend, research institutions and agricultural development programs have promoted a variety of soil fertility management practices tailored to local conditions (Mugwe et al., 2009). These practices primarily include the application of mineral fertilizers, animal manure, compost, and green manure crops. The goal is to restore soil health, increase nutrient availability, and create favorable conditions for plant growth. Farmers can opt for a singular approach (using either organic or inorganic fertilizers), or they may adopt an integrated strategy that combines both, depending on their resources and environmental conditions.

Integrated Soil Fertility Management (ISFM) is particularly emphasized in modern sustainable agriculture as it combines scientific knowledge and local innovations. The blending of organic and inorganic soil amendments has been shown to significantly improve soil structure, enhance microbial activity, and increase nutrient retention (Vanlauwe et al., 2010). Organic materials such as compost and animal manure contribute to the improvement of soil physical properties and the gradual release of nutrients. Meanwhile, mineral fertilizers offer a quicker supply of essential macronutrients such as nitrogen, phosphorus, and potassium. The synergy between these amendments improves the efficiency of nutrient uptake by plants, leading to improved crop yields and long-term soil resilience. ISFM is now recognized not just for its productivity benefits but also for its role in climate adaptation and environmental conservation.

Water harvesting technologies, such as zai pits, are especially effective when applied to soils that have already undergone fertility enhancement. As Sanchez et al. (1997) argue, the profitability and effectiveness of water harvesting methods increase when the soil is fertile, as plants are better able to respond to available moisture when essential nutrients are present. Therefore, it is not sufficient to focus solely on water availability; equal attention must be paid to restoring soil fertility to maximize returns. This underscores the need for a combined approach where investments in soil amendments are paired with conservation techniques like zai pits, terraces, or bunds. When used together, these methods can break the vicious cycle of low productivity and land degradation in ASALs, paving the way for resilient farming systems.

Empirical studies support the efficacy of this combined approach. Barry et al. (2019) documented substantial improvements in soil texture and fertility through the use of zai pits complemented with organic and inorganic amendments. Their research demonstrated an increase in the soil's clay content and a reduction in the sand fraction, both indicators of improved soil structure. These changes enhance the soil’s water-holding capacity and its ability to retain nutrients, which are critical for sustaining crop growth during dry spells. The zai method, by concentrating runoff and nutrients in one location, acts as a localized fertility hotspot that accelerates biomass production and boosts microbial activity. Over time, this contributes to the gradual rehabilitation of poorly structured or degraded soils.

The biological and physical benefits of improved soil fertility also extend to ecosystem restoration. Soils amended with compost or manure tend to have higher carbon content, which improves their structure and makes them more resilient to erosion and compaction. Additionally, the zai method, when paired with manure or compost, increases microbial biodiversity and improves the cation exchange capacity of the soil, further promoting sustainable land management (Nyamangara et al., 2013). These practices not only support agricultural productivity but also contribute to broader ecological benefits such as carbon sequestration, enhanced biodiversity, and reduced greenhouse gas emissions.

Therefore, the objective of this study is to evaluate the influence of zai pits in combination with different soil fertility amendment options on overall soil quality and productivity in ASAL regions. By analyzing various combinations of organic and inorganic inputs in conjunction with zai technology, this research aims to identify the most efficient and scalable approaches for soil restoration. This is particularly critical for communities dependent on rain-fed agriculture and vulnerable to the impacts of climate change. The integration of soil fertility amendments with water harvesting technologies offers a holistic pathway to rehabilitate degraded lands, improve crop yields, and ensure the sustainability of smallholder farming systems in Kenya and beyond.

Furthermore, the integration of modern soil fertility practices, such as the incorporation of biochar or composting, has gained significant attention due to their positive effects on soil structure and microbial activity. These methods can further enhance the impact of zai pits by improving soil aeration, increasing organic matter content, and fostering the growth of beneficial soil organisms. As a result, these techniques not only contribute to better soil fertility but also enhance the long-term sustainability of farming systems by promoting ecological balance and reducing dependency on chemical fertilizers. Additionally, research on the combined use of organic amendments and zai pits can provide valuable insights into how smallholder farmers in resource-constrained environments can optimize their farming practices for better productivity and environmental stewardship.

2.3 Factors that Influence the Adoption of Zai Pits

The implementation and application of water harvesting techniques are critical for advancing agricultural productivity, particularly in arid and semi-arid lands (ASALs). These methods help optimize the use of limited water resources by capturing, storing, and concentrating rainwater and surface runoff. Among them, the zai pit technique stands out due to its ability to rehabilitate degraded lands and enhance crop yields. According to Amsalu and De Graaff (2017), the adoption of zai pits is shaped by a combination of socio-cultural, economic, and biophysical factors, which tend to vary across locations and households. The diversity in farming systems and resource availability means that the success of adoption cannot be generalized but must instead be understood through localized assessments. Kessler (2016), Giller et al. (2019) and Kassie et al. (2020) all emphasize that adoption patterns often yield conflicting outcomes due to the dynamic nature of environmental and socio-economic contexts across regions.

In a study conducted in 2000 in Northern Burkina Faso, Slingerland and Stork found that farmers who embraced zai pits tended to have relatively larger family sizes, greater access to transport, and a higher number of livestock. These characteristics are directly related to the labor-intensive and input-demanding nature of zai pits, which require organic matter such as manure for optimal performance. The availability of livestock ensures a consistent supply of manure, while improved transportation options facilitate the movement of soil amendments and harvested crops. This reflects the importance of household assets in influencing adoption decisions, particularly in regions where external support systems are limited or non-existent.

On the other hand, certain barriers hinder widespread adoption. Goderniaux et al. (2015) found that in many parts of Sub-Saharan Africa, farmers lacked adequate knowledge about soil erosion processes and the benefits of soil and water conservation techniques like zai pits. Furthermore, limited access to critical resources such as organic manure, labor, agricultural tools, and transportation infrastructure significantly reduces the likelihood of adoption. These limitations are particularly pronounced among resource-poor households that struggle to meet the initial labor and input requirements needed to implement zai pits effectively.

Education and awareness are also critical drivers. Zongo et al. (2015) reported that in Northern Burkina Faso, farmers with higher educational attainment and a better understanding of soil degradation were more likely to adopt zai pits. Education enhances awareness of environmental risks and the long-term benefits of conservation practices, thereby fostering positive attitudes toward sustainable agriculture. Additionally, educated farmers are more likely to access extension services, understand technical recommendations, and integrate innovations into their farming systems.

Institutional support plays a pivotal role in scaling up zai pit adoption. In a study conducted in Malawi and Zambia, Ndah et al. (2014) highlighted the significance of favorable institutional frameworks in promoting sustainable land management. Factors such as an active agricultural extension system Nyanga (2012) and the implementation of the lead farmer model Haggblade and Tembo (2015) were identified as essential in disseminating knowledge and skills to other farmers. The presence of well-coordinated support structures enables the exchange of experiences and creates a multiplier effect, accelerating the adoption of zai pits at the community level.

Gender dynamics and land tenure arrangements also influence adoption decisions. In patriarchal societies, women may have limited access to land or the authority to make decisions regarding soil and water conservation investments. Studies have shown that female-headed households are less likely to adopt zai pits due to reduced access to labor and extension services (Kassie et al., 2020). Moreover, insecure land tenure discourages long-term investments like zai pits, which require significant initial effort and whose benefits accrue over time. Addressing these structural constraints is vital to ensure equitable adoption and impact across diverse demographic groups.

Interestingly, while zai pits are most commonly associated with Sub-Saharan Africa, aspects of this technique have attracted interest in developed countries under the lens of regenerative agriculture. In the United States, for example, farmers experimenting with micro-catchment basins and bio-intensive gardening techniques in arid states like Arizona and New Mexico are employing modified versions of the zai concept to enhance water retention and soil fertility on small-scale plots. These systems incorporate compost and mulch into shallow pits or basins, mimicking the water and nutrient-concentrating properties of traditional zai pits. Though mechanized and adapted for smaller garden plots, these approaches align with broader sustainable land management goals in water-scarce regions of developed nations (La Rosa et al., 2020). This signals the global applicability of indigenous innovations when integrated with modern agro-ecological practices.

Another critical factor influencing the adoption of zai pits is the presence of social networks and farmer-to-farmer knowledge exchange. In many rural areas, farmers often rely on their peers for advice and information about new farming practices, including water conservation technologies like zai pits. The influence of local leaders, such as village chiefs or successful farmers, can play a significant role in shaping attitudes toward adoption. Moreover, farmer groups and cooperatives can provide a platform for collective action, allowing farmers to share resources, labor, and knowledge, which can lower the costs associated with the initial adoption of zai pits and increase the likelihood of successful implementation.

2.4 Effects of Zai Pits on Soil Moisture

Water harvesting and moisture retention are foundational to the survival and productivity of crops, especially in semi-arid and arid environments where rainfall is highly erratic. Zai pits have emerged as a resilient and effective technology for enhancing soil water retention. These micro-catchment basins allow rainwater to be harvested directly where crops are planted, improving the availability of water precisely at the root zone. As highlighted by Stott et al. (2001), zai pits slow down the movement of water, enabling infiltration and minimizing evaporation, particularly in the early stages of plant growth. This local concentration of water helps maintain a more favorable microclimate for seedlings, increasing their chances of establishment and survival during dry periods.

Nyamadzawo et al. (2013) observed that zai pits serve as buffers against prolonged dry spells by maintaining soil moisture levels for extended periods. The water stored in these pits delays the onset of water stress symptoms in crops, acting as a protective mechanism that supports plant physiological functions during drought conditions. This buffering effect is especially critical in environments with short and unpredictable rainy seasons, where a few missed rains can lead to total crop failure. The pits essentially create small reservoirs that ensure water is available for crops even after rainfall has ceased, thus promoting greater drought resilience.

Further, zai pits not only enhance water storage but also improve water infiltration and reduce surface runoff. Their structure allows for deeper percolation of water into the soil profile, which in turn improves water uptake by plant roots. Dreschel et al. (2005) reported that this technique significantly enhances moisture retention in the soil by limiting water loss through runoff and evaporation. Malesu et al. (2006) supported this by estimating that zai pits can capture up to 25% or more of surface runoff from an area approximately five times larger than the pit itself. This redirection and capture of water significantly contribute to maintaining soil moisture during extended dry periods.

Critchley and Gowing (2012) emphasized the critical role of zai pits in ensuring crop success in areas frequently plagued by crop failures due to water scarcity. By enhancing soil water retention, the technique supports the consistent growth of crops, even in seasons characterized by below-average rainfall. Moreover, the pits are often filled with organic materials such as manure and compost, which further increase water-holding capacity and improve soil structure. These organic inputs enhance the soil's sponge-like characteristics, enabling it to retain more water and nutrients, which directly benefits plant growth and resilience.

In addition to water retention, zai pits improve soil health and facilitate the gradual rehabilitation of degraded land. Over time, repeated use of zai pits contributes to the build-up of organic matter, microbial activity, and root penetration, all of which enhance soil porosity and water infiltration rates. This regeneration of soil function results in long-term improvements in the water cycle and ecosystem services in the area. According to Kaboré and Reij (2016), widespread adoption of zai pits in the Sahel has led to significant re-greening and improvement in previously barren landscapes, largely attributed to improved soil moisture conditions.

The effectiveness of zai pits is also evident when combined with other soil and water conservation techniques. When used alongside contour bunds, mulch, or half-moon structures, zai pits form part of an integrated water management system that maximizes water availability. In areas prone to frequent drought, such combinations can make the difference between a failed harvest and food security. The current investigation focuses on evaluating the synergistic influence of zai pits integrated with both organic and inorganic amendments to boost moisture preservation in drought-prone areas, further emphasizing the adaptability and scalability of the technique across various ecological zones.

Interestingly, water-harvesting innovations akin to zai pits are gaining attention in developed nations, particularly in regions facing the impacts of climate change and water scarcity. For instance, in the southwestern United States, urban agriculture practitioners and regenerative farmers are using techniques such as swales, rain gardens, and basin planting—concepts inspired by traditional practices like zai pits—to maximize rainfall capture and infiltration These approaches are used to mitigate urban flooding and improve resilience in backyard and community gardens. Although implemented in a modern context with the aid of design tools and advanced materials, these practices reflect the same core principle of harvesting water in situ to enhance soil moisture and reduce reliance on irrigation systems.

In addition to the immediate benefits of improved water retention, zai pits can also help mitigate the negative effects of soil erosion, which is a common problem in many semi-arid regions. By creating small depressions in the ground, zai pits reduce the velocity of surface runoff, allowing water to infiltrate the soil more efficiently. This reduction in erosion helps maintain soil depth and structure, preventing further degradation of the land. Furthermore, the stabilization of soil aggregates through the use of zai pits can increase soil resilience to both waterlogging and drought, providing a more stable environment for plant roots and contributing to the overall sustainability of the farming system.

2.5 Impact of Zai Pits on Yields

Zai pits have shown significant potential in improving crop yields, especially in dryland agricultural systems where water scarcity and soil degradation pose major challenges. In Burkina Faso, for example, the implementation of zai pits in the village of Donsin resulted in a notable yield increase of 310 kg per hectare for sorghum compared to control plots without zai pits (Kaboré & Reij, 2016). This yield enhancement is attributed to the micro-catchment nature of the zai pits, which improves moisture availability, promotes root development, and reduces crop stress during dry spells. Such yield benefits have inspired widespread adoption among smallholder farmers in the Sahel.

A long-term study conducted from 1991 to 1996 in the Illela district of Niger further demonstrated the benefits of zai pits on cereal yields. Farmer-managed fields that utilized zai pits achieved an average yield of 513 kg ha^{-1}, substantially higher than the 125 kg ha^{-1} recorded in untreated plots (Kaboré & Reij, 2016). Yield variation over the six years ranged from 297 kg ha^{-1} in 1992 to an impressive 969 kg ha^{-1} in 1994, illustrating both the productivity gains and variability linked to annual rainfall and management practices. This consistent trend in increased yields supports the potential of zai pits as a low-cost, scalable strategy for boosting food security in dryland regions.

In Kenya, Muyekho et al. (2000) examined the application of zai pits—locally referred to as Tumbukiza in western Kenya and found them to be highly effective in increasing dry matter yields. Compared to conventional flat planting methods, the Tumbukiza approach allowed for better water retention and nutrient concentration around the root zone, which translated into improved crop biomass and grain production. The technique has since gained traction in other Kenyan counties, especially in areas that experience recurrent drought and soil infertility. Farmers reported more robust and uniform crop stands, which contributed to better harvest predictability.

Despite their labor-intensive nature, many farmers consider the benefits of zai pits to outweigh the costs. Rockström at el. (2018) noted that, farmers frequently express confidence in the investment of time and labor required to dig and maintain zai pits due to the increased yields and reduced risk of crop failure. However, Barry et al. (2019) caution that while substantial anecdotal and experimental evidence supports yield improvements, there remains a dearth of comprehensive economic evaluations to understand the full cost-benefit implications of adopting zai pits at scale. Understanding these financial aspects is crucial for encouraging broader adoption and policy support.

In semi-arid zones where seasonal droughts are common, zai pits can mean the difference between total crop loss and a modest harvest. A study conducted in Zambia Haggblade and Tembo (2015) found that planting basins similar to zai pits enabled farmers to maintain crop production even under conditions of extremely low rainfall. The pits functioned not only as water harvesters but also as nutrient traps, especially when organic matter was added. In five villages located in the northern region of the Central Plateau of Zambia, Kaboré and Reij (2016) reported that communities unanimously acknowledged the role of zai pits and other soil water conservation techniques in sustaining household food supplies, even during poor seasons.

Nonetheless, it is important to acknowledge the limitations of zai pits. Bationo et al. (2006) reported that the application of zai pits alone, without supplemental inputs like organic manure or fertilizers, often led to minimal yield improvements. Their findings in West Africa indicated that sorghum grain yields increased only marginally, reaching 200 kg ha^{-1}. These results suggest that while zai pits improve water retention, optimal yield outcomes require integrated soil fertility management practices, including the use of compost, farmyard manure, or mineral fertilizers to replenish nutrient-depleted soils.

Interestingly, concepts inspired by zai pits are now being explored in dryland regions of developed countries. In Australia, for instance, conservation agriculture and precision water harvesting technologies such as contour planting and micro-basins are gaining popularity in drought-prone zones like Western Australia and New South Wales (Hatfield & Prueger, 2015). These methods, though technologically advanced and mechanized, are based on the same principle of concentrating moisture and nutrients around plant roots to optimize yields under water-limited conditions. While the context differs, the shared goal of maximizing productivity through efficient water management highlights the global relevance and adaptability of zai pit-inspired innovations.

Moreover, the long-term benefits of zai pits extend beyond immediate yield improvements. The continued use of zai pits can lead to gradual soil improvement, as the accumulation of organic matter and nutrients in the pits contributes to the overall soil health. Over time, this can result in more consistent crop yields and greater resilience to environmental stresses such as drought, soil erosion, and nutrient depletion. However, to realize these long-term benefits, it is essential that farmers maintain proper management practices, including regular maintenance of the zai pits, addition of organic inputs, and appropriate crop rotation strategies. This sustainable approach ensures that the practice of using zai pits continues to benefit both farmers and the environment in the years to come.

2.6 Conventional Farming and Yields

Conventional farming, characterized by the use of synthetic fertilizers, pesticides, and mechanized equipment, has long been regarded as the cornerstone of modern agricultural practices. This method is often associated with high yields, particularly in regions with favorable climatic conditions and sufficient water resources. The use of chemical inputs in conventional farming helps to overcome soil deficiencies and control pests, leading to increased crop productivity (Sanchez et al., 2009). However, the sustainability of conventional farming practices has been questioned due to concerns over environmental degradation, soil fertility decline, and over-reliance on external inputs (Balmford et al., 2018).

One of the key advantages of conventional farming is its ability to produce high yields in the short term. The application of synthetic fertilizers provides immediate nutrients to crops, promoting rapid growth and higher crop yields (Tilman et al., 2002). In many developed countries, conventional farming has contributed to substantial increases in food production, helping to meet the growing demand for food. For instance, the use of synthetic nitrogen fertilizers has significantly boosted the yields of staple crops like maize, wheat, and rice, which are essential to global food security (Zhang et al., 2015). In addition, mechanization in conventional farming allows for more efficient land cultivation, planting, and harvesting, reducing labor costs and increasing overall productivity.

Despite its yield benefits, conventional farming has faced criticism for its negative impact on soil health. Continuous use of synthetic fertilizers can lead to soil acidification, nutrient imbalances, and a decrease in soil organic matter, which are detrimental to long-term soil fertility (FAO, 2016). This depletion of soil quality often results in reduced yields over time, especially in regions where intensive farming practices are not complemented by sustainable soil management practices. Furthermore, the reliance on pesticides in conventional farming can harm beneficial soil organisms, leading to a decline in biodiversity and reduced natural pest control services (Altieri, 1999). Such ecological imbalances may ultimately lower yields in the long term, undermining the very productivity that conventional farming initially promises.

Environmental concerns are compounded by the fact that conventional farming is often not well-suited to arid and semi-arid regions, where water scarcity and soil degradation pose significant challenges. In these regions, the use of excessive irrigation and the application of chemical fertilizers can exacerbate water pollution and salinization of the soil (Mati, 2005). For instance, in semi-arid areas of Sub-Saharan Africa, conventional farming has led to a decrease in the availability of water resources, as irrigation systems often waste large amounts of water, further intensifying the challenges posed by drought (Reij et al., 2009). While conventional farming methods may yield well in the short term, these environmental impacts can significantly reduce productivity over time, highlighting the need for more sustainable agricultural practices in water-scarce regions.

Conventional farming has proven effective in achieving high yields, especially in regions with favorable climatic conditions and adequate resources. However, the long-term sustainability of this approach is increasingly being questioned due to its environmental costs, such as soil degradation, water pollution, and biodiversity loss. While conventional farming can boost yields in the short term, it requires careful management and complementary practices to ensure soil health and productivity are maintained over time. Without such adjustments, the yield advantages of conventional farming may diminish, especially in areas facing the challenges of climate change and resource depletion.

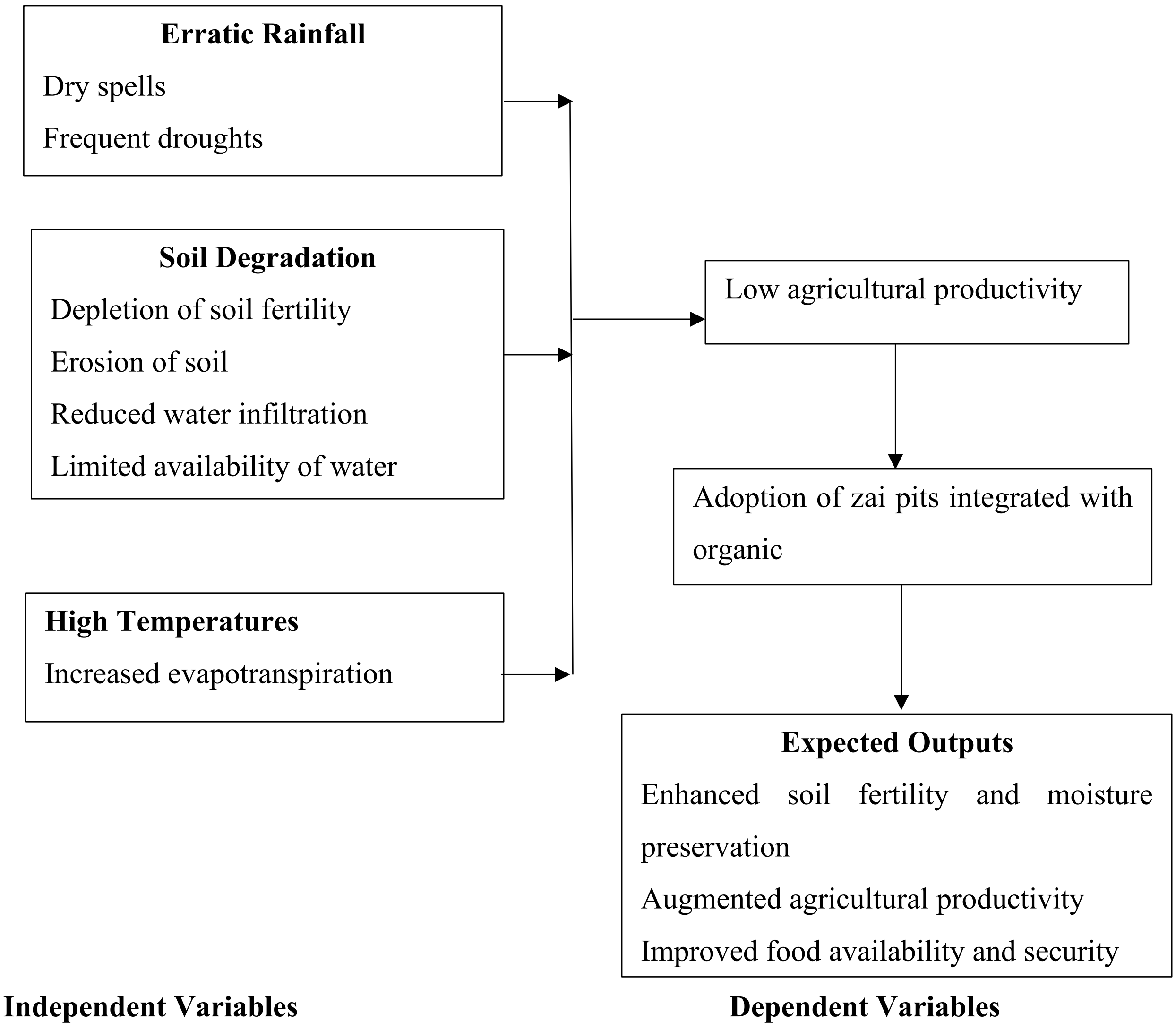
Additionally, the increased dependency on external inputs such as synthetic fertilizers and pesticides in conventional farming has raised concerns about food safety and human health. The residues of pesticides and chemical fertilizers in food products can pose health risks to consumers, including the development of antibiotic resistance, hormonal disruptions, and potential carcinogenic effects (BfR, 2016). Furthermore, the long-term exposure of farmworkers to these chemicals has been linked to a range of health problems, including respiratory issues, skin disorders, and neurological damage (Sørensen et al., 2017). These health implications have spurred growing interest in alternative farming practices that minimize or eliminate the use of chemical inputs, such as organic farming and integrated pest management. While conventional farming may continue to be the dominant agricultural system globally due to its yield potential, these health and environmental risks underscore the need for greater emphasis on sustainable farming practices that balance productivity with ecological and human well-being.

2.7 Conceptual Framework

Crop productivity in semi-arid regions is severely constrained by low and unpredictable rainfall, nutrient-deficient soils, and high temperatures. The presence of demanding environmental circumstances, especially in combination with inadequate water availability, greatly restricts the potential to attain substantial crop yields. The accompanying image illustrates the impacts of water harvesting techniques, such as zai pits.

Figure 2.1

Conceptual Framework



2.8 Summary and Research Gaps

Despite the growing body of evidence supporting the efficacy of zai pits in enhancing agricultural productivity, particularly in arid and semi-arid regions, their widespread adoption remains limited. Several global and regional initiatives have promoted zai pits as a sustainable solution to pressing challenges such as water scarcity, land degradation, and low crop yields. However, as Falkenmark et al. (2018) and Barry et al. (2019) observed, many smallholder farmers continue to underutilize this technique. This paradox highlights the complex nature of technology adoption in rural settings, where socio-economic, cultural, and institutional barriers often impede the uptake of innovative practices, regardless of their proven benefits.

In the context of Kenya's low midland agro-ecological zones, such as Maragua Sub-County and Mbeere South Sub County, the adoption of zai pits is notably low despite evidence from regions like Burkina Faso, Niger, and Western Kenya that demonstrates their potential to boost yields and build resilience against drought (Kaboré & Reij, 2016; Muyekho et al., 2000). This underutilization calls for localized investigations to better understand the socio-ecological and economic determinants that influence adoption behaviors. The absence of tailored extension services, limited access to organic inputs, labor demands, and farmer perceptions could all be contributing factors. Yet, these aspects remain largely unexamined in the study area, presenting a significant research gap.

Moreover, existing studies have predominantly focused on staple cereals such as sorghum and millet when assessing the impact of zai pits. There is scant information on how this technology performs with leguminous crops like green grams, particularly when integrated with organic soil amendments. Given the increasing importance of legumes in enhancing soil fertility through nitrogen fixation and improving household nutrition and income, it is imperative to investigate how zai pits influence green gram performance in the Kenyan context.

This study, therefore, seeks to evaluate the influence of zai pits on critical aspects of soil fertility, including nutrient rejuvenation, soil moisture retention, and the structural integrity of soil aggregates. These components are essential for long-term land productivity, yet they are rarely measured in field conditions where zai pits are employed. By incorporating organic inputs such as compost or farmyard manure into the zai pits, this study also aims to explore the synergistic effects of water harvesting and fertility enhancement—a combination that has shown promise in other contexts but has not been adequately explored in Kenya’s low midland regions.

Additionally, while numerous studies acknowledge yield improvements from zai pits, there is a lack of quantifiable data linking these improvements to specific soil fertility parameters. This limits the ability of policymakers and extension agents to develop evidence-based recommendations for farmers. The study also seeks to address this knowledge gap by establishing empirical relationships between zai pit use, soil fertility changes, and green gram yields over a growing season.

In summary, this research responds to a dual need: understanding why farmers are hesitant to adopt zai pits and providing scientific evidence on their agronomic benefits when paired with organic amendments. By bridging these knowledge gaps, the study will contribute valuable insights that can inform targeted interventions, improve extension messaging, and promote the sustainable intensification of smallholder agriculture in dryland Kenya.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

The research design, target population, sampling, data collection techniques, approaches to data analysis, description of the experiment site, and green gram agronomic practices will all be covered in this section.

3.2 Site Description

The research was carried out in Maragua Sub County, Murang'a County, and Mbeere South Sub County, Embu County, Kenya. Maragua Constituency was one of seven seats in Murang'a County, bordering to the east by Machakos County, to the northeast by Embu County, to the north by Kiharu Constituency, to the south by Gatanga Constituency, and to the west by Kandara and Kigumo constituencies. Mbeere South Subcounty was situated in Embu County, adjacent to Tharaka Nithi County to the north, Kitui County to the east, Machakos County to the south, and Murang'a County to the southwest.

Figure 3.1

Study area

The study area recorded an average yearly temperature of 21.49ºC (70.68ºF), which was 1.01% lower than Kenya's average. Maragua typically received about 124.89 millimeters (4.92 inches) of precipitation and experienced approximately 204.36 rainy days (55.99% of the time) annually, as indicated by *Maragua, Murang'a, KE Climate Zone, Monthly Averages, Historical Weather Data* (n.d.). According to the Farm Management Handbook of Kenya (2012), the study area had volcanic footridges and fertile but highly erodible and depleted soils. Similar climatic conditions were recorded in Mbeere South Subcounty.

3.3 Research Design

The study adopted Randomized Complete Block Design (RCBD). Three blocks was created with 8 treatments replicated two times. At each site, a total of 48 sub-plots was used.

3.4 Field Establishment and Treatment Applications

This section highlights the procedures that used for land preparation, the treatments that was used which include Use of Zai Pits and Manure, Use of Zai Pits and Mulch, Use of Zai Pits, Manure, and Mulch, Use of Zai Pits Alone, Conventional Farming Alone, Conventional Farming with Manure, Conventional Farming with Mulch, and Conventional Farming with Mulch and Manure.

3.4.1 Land Preparation

The land was first undergone meticulous clearing of debris and levelling to ensure uniformity across all experimental plots. This step is crucial to minimize any potential variations in environmental factors that could influence the study's outcomes. Additionally, soil testing may be conducted to evaluate the initial soil properties and nutrient levels, providing valuable baseline information for the experiment.

3.4.2 Treatments and Applications

The experiment involves testing various treatments to evaluate their effects on the growth and yield of green grams production. Each treatment is carefully applied to designated experimental plots, allowing for comparisons and analysis of their impact relative to one another.

Use of Zai Pits and Manure

Experimental plots were prepared with both zai pits and the application of manure. Zai pits are small planting holes dug into the soil, designed to improve water infiltration and retention, while manure serves as a source of organic nutrients to enrich the soil and support plant growth.

Use of Zai Pits and Mulch

Experimental plots integrate zai pits with a layer of mulch on the soil surface. Mulch, including straw, leaves, or plastic sheeting, aids in conserving soil moisture, inhibiting weed growth, and regulating soil temperature. When utilized alongside zai pits, mulch can augment soil moisture retention and increase overall cultivation circumstances.

Use of Zai Pits, Manure, and Mulch

Experimental plots feature the integration of zai pits, manure, and mulch. This comprehensive approach combines the benefits of improved soil structure from zai pits, nutrient enrichment from manure, and enhanced soil moisture conservation and weed suppression from mulch.

Use of Zai Pits Alone

Experimental plots focus solely on the implementation of zai pits without any additional treatments. This allows researchers to evaluate the standalone effects of zai pits on soil properties, water dynamics, and plant growth without confounding factors from other treatments.

Conventional Farming Alone

Experimental plots follow conventional farming practices without the use of zai pits or additional treatments. This treatment serves as a control group, providing a baseline for comparison with other treatments and assessing the relative effectiveness of zai pit-based approaches.

Conventional Farming with Manure

Experimental plots employ conventional farming methods supplemented with the application of manure. This treatment aims to evaluate the impact of organic nutrient supplementation within conventional farming systems on soil fertility and crop productivity.

Conventional Farming with Mulch

Experimental plots utilize conventional farming techniques alongside the application of mulch. This treatment explores the benefits of mulch in conventional farming systems, such as weed control, moisture conservation, and soil temperature moderation, and their implications for crop production.

Conventional Farming with Mulch and Manure

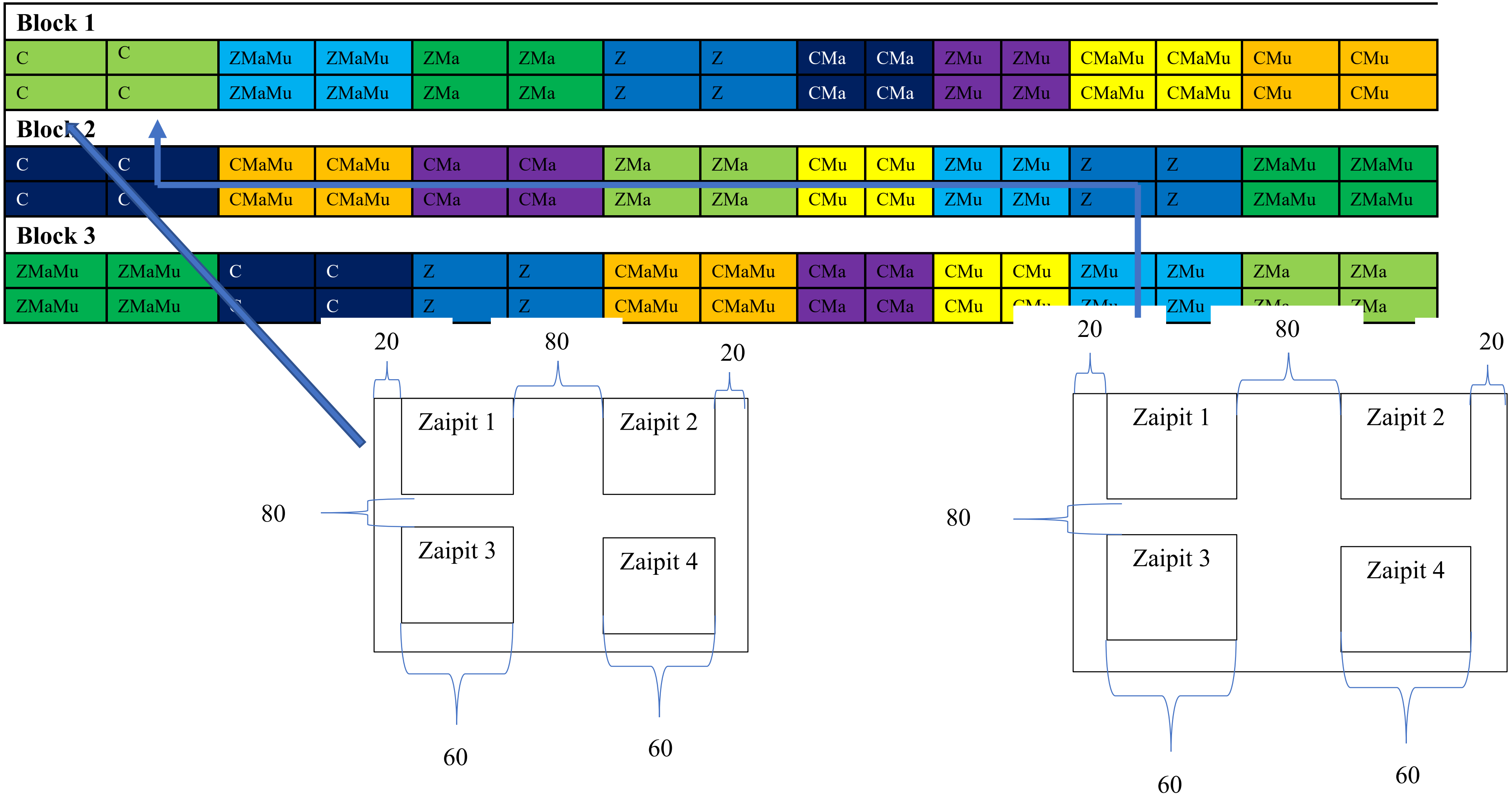
Experimental plots implement conventional farming practices while incorporating both mulch and manure. This combined approach assesses the interactive effects of mulch and manure within conventional farming systems, potentially enhancing soil health, nutrient cycling, and overall crop productivity.

3.5 Experimental Layout

Figure 2 below illustrates the physical arrangement of the experimental plots, depicting the layout of the two replicates with their respective experimental units. Each replicate consists of eight main plots. The total number of plots per experimental site will 16, resulting in 96 sub-plots due to the division of each plot into two sub-plots to accommodate the 8 varieties; this design will represent a split-plot design. With 8 treatments across 6 replicates, the total number of experimental configurations is 48. Each plot measures 2 meters by 2 meters, while each sub-plot has treatments applied within an area of 60 cm by 60 cm, with a spacing of 80 cm by 20cm between each treatment. This was done in both study area Maragua sub -County and Mbeere South Sub-County.

Figure 3. 1

Physical Arrangement of Experimental Units



Block 1

C	C	ZMaMu	ZMaMu	ZMa	ZMa	Z	Z	CMa	CMa	ZMu	ZMu	CMaMu	CMaMu	CMu	CMu
C	C	ZMaMu	ZMaMu	ZMa	ZMa	Z	Z	CMa	CMa	ZMu	ZMu	CMaMu	CMaMu	CMu	CMu

Block 2

C	C	CMaMu	CMaMu	CMa	CMa	ZMa	ZMa	CMu	CMu	ZMu	ZMu	Z	Z	ZMaMu	ZMaMu
C	C	CMaMu	CMaMu	CMa	CMa	ZMa	ZMa	CMu	CMu	ZMu	ZMu	Z	Z	ZMaMu	ZMaMu

Block 3

ZMaMu	ZMaMu	C	C	Z	Z	CMaMu	CMaMu	CMa	CMa	CMu	CMu	ZMu	ZMu	ZMa	ZMa
ZMaMu	ZMaMu	C	C	Z	Z	CMaMu	CMaMu	CMa	CMa	CMu	CMu	ZMu	ZMu	ZMa	ZMa

Key		Z	Use of Zai Pits Alone
ZMa	Use of Zai Pits and Manure	C	Conventional Farming Alone
ZMu	Use of Zai Pits and Mulch	CMa	Conventional Farming with Manure
ZMaMu	Use of Zai Pits, Manure, and Mulch	CMu	Conventional Farming with Mulch
CMaMu	Conventional Farming with Mulch and Manure		

3.6 Sampling Procedure

The target population in this study was comprised of all the green gram plants across the 48 plots to which the results of the sample analysis was generalized. The size of the target population per experimental site was 864 green gram plants.

3.7 Data Collection

This section highlights the data which was collected during the experimental period. These was including green gram growth parameters and yield.

3.7.1 Plant Height Measurement

The height of tagged plants in each plot was measured using a measuring tape, from the base of the stem to the tip of the top leaf. This measurement was provided insights into the growth of green gram plants under different experimental conditions.

3.7.2 Plant Stem Girth Measurement

The stem girth of green gram plants was measured at the base of the stem using a Vanier caliper. This measurement was captured the thickness or diameter of the stem, providing information about the plant's structural development and potential biomass production.

3.7.3 Number of Branches

The number of branches in green gram was assessed by systematically counting the branches extending from the main stem of each plant. This process ensures an accurate understanding of the branching pattern and structural development of green gram plants. Analysis of this data provides valuable insights into the plant's growth dynamics and potential yield.

3.7.4 Grain yield of Green Gram

At the maturity stage of the 8 evaluated green gram treatment, the assessment of grain yield was conducted. This comprehensive process involves uprooting 5 tagged plants from each plot, followed by the harvesting of pods. The pods will then undergo threshing to separate the grains. After threshing, the first measurement of grain yield will occur, where the weights of the grains were recorded using a digital weighing balance, measured in kilograms. Subsequently, the grains were dried to eliminate moisture content. After drying, the second measurement of grain yield was conducted using the same digital weighing balance. This sequential approach ensures an accurate assessment of the final grain yield, accounting for moisture loss during drying.

3.8 Data Management and Statistical Analysis

The analysis and data management for the collected data was conducted using SPSS (Statistical Package for the Social Sciences) version 25.

Firstly, the collected data on green gram growth parameters and yield, including plant height, stem girth, number of branches, and grain yield, was entered into SPSS. Each variable was assigned appropriately labelled variables within the software to ensure organization and clarity. Once the data is entered, descriptive statistics such as mean, standard deviation, and frequency distributions was computed to summarize the characteristics of the data set. This will provide an overview of the central tendency and variability of the measured variables.

Next, inferential statistical analyses was performed to examine relationships and differences between variables. For example, correlation analyses may be conducted to assess the relationship between plant height, stem girth, and grain yield. Additionally, analysis of variance (ANOVA) tests may be used to determine if there are significant differences in growth parameters and yield among different experimental conditions or varieties.

Furthermore, regression analyses may be employed to model the relationship between predictor variables (e.g., plant height, stem girth) and the outcome variable (grain yield), allowing for prediction and interpretation of the factors influencing yield.

Finally, the results of the analysis were interpreted and presented in a clear and understandable format, using tables, graphs, and statistical summaries. This will facilitate the communication of findings and insights from the study, enabling informed decision-making and further research in the field of green gram production.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the study, organized according to the research objectives. The aim was to examine how zai pits, mulch, and manure influence the growth and yield of green grams. The findings are discussed in light of key agronomic indicators such as plant height, stem girth, number of leaves, and number of pods per plant. The chapter begins by assessing the combined effects of zai pits, mulch, and manure on green gram production, providing insight into how these soil and water conservation practices interact to influence plant growth and productivity.

The second part of the chapter focuses on the effects of mulch and manure when applied with or without zai pits. This section aims to distinguish the individual and combined roles of mulch and manure in enhancing crop performance, while also evaluating their effectiveness in the presence or absence of zai pits. The third section compares the influence of zai pits to conventional farming practices, offering a clear picture of the added value that zai pit technology may bring to green gram production, especially under dryland conditions.

Finally, the chapter includes a detailed discussion of the findings in relation to existing literature and theoretical frameworks. Each research objective is revisited in the discussion section to interpret the results, identify trends, and explore the practical implications for smallholder farmers. Through this analysis, the chapter contributes to a deeper understanding of sustainable agricultural practices and their potential to improve green gram yields in semi-arid areas.

4.2 Assessment of the Effects of Zai Pits, Mulch and Manure on the Growth parameters on the Green Grams Production

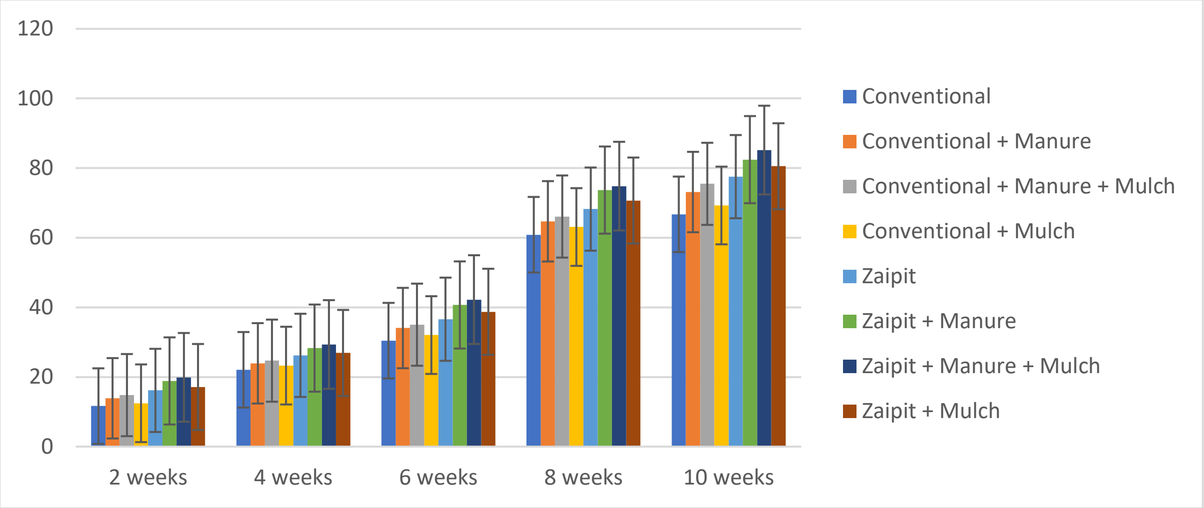
The effect of zai pits, mulch, and manure on the growth of green grams was evaluated using three key growth parameters: plant height, stem girth, and number of leaves. These measurements were taken biweekly from five tagged plants per plot throughout the growth cycle.

4.2.1 Plant height

Plant height was measured using a meter rule, stem girth using vernier calipers, and the number of leaves by direct counting. The results, as illustrated in Figure 4.1, clearly demonstrate that the tallest plants were recorded under the combined treatment of zai pit, manure, and mulch, while the shortest were observed under the conventional farming method with no amendments. This indicates a positive synergistic effect of integrating zai pits with organic inputs on plant vigor.

Figure 4.1

Plant Height at Different Weeks for Zai Pit with or Without Mulch or Manure



Effect of growth was assessed using plant height, girth and number of leaves and different weeks after planting. These parameters were taken every 2 weeks on 5 tagged plants per plot. Plant height was measured using a meter rule; girth diameter was measured using vernier callipers, while number of leaves was determined by counting the leaves. A summary of the data collected is given in Figures 4.1. for plant height; 4.2 for Girth diameter; and 4.3 for number of leaves.

Table 4. 1

ANOVA Summary for the Effect of the Treatments on Plant Height

Tests of Between-Subjects Effects
Dependent Variable: Height (cm)

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Treatment	1577.026	7	225.289	607.868	.000
Block	.922	2	.461	1.244	.300
Site	.088	1	.088	.236	.630
Error	13.713	37	.371		
Total	1591.748	47			

a. R Squared = .991 (Adjusted R Squared = .989)

To statistically assess whether the observed differences in plant height were significant across the different treatments, an ANOVA test was conducted. The results, presented in Table 4.1, revealed that the treatments had a statistically significant effect on plant height ($p < 0.001$), whereas site and block effects were not significant, indicating consistency in the treatment response across the experimental conditions. The high R-squared value (0.991) further confirms that the model explains almost all the variation in plant height due to treatment differences.

As can be seen from Table 4.1, the sites and the blocks did not have significant differences (p values of 0.300 and 0.630 respectively) while the treatments had significant differences (p less than 0.01). For this reason, the treatment means were compared using posthoc to determine which ones are significantly different and the results are summarized in Table 4.2.

Table 4. 2

Post Hoc Analysis Summary for the Effect of the Treatments on Plant Height

Treatment	**Height (cm)**
Conventional	67.280a
Conventional + Mulch	70.048b
Conventional + Manure	72.460c
Conventional + Manure + Mulch	74.973d
Zaipit	77.647e
Zaipit + Mulch	80.135f
Zaipit + Manure	82.355g
Zaipit + Manure + Mulch	84.830h

A post hoc analysis was then carried out to determine which treatment means differed significantly from each other. The results, summarized in Table 4.2, show a clear gradation in plant height across the treatments. The conventional treatment recorded the lowest mean plant height (67.28 cm), while the highest mean (84.83 cm) was observed under the zai pit + manure + mulch treatment. Intermediate values were recorded for other treatment combinations, with a consistent trend showing that the inclusion of zai pits, either alone or in combination with organic amendments, led to progressively taller plants. Each treatment group was significantly different from the others, as denoted by different letters in the post hoc comparison, reinforcing the conclusion that zai pits and organic inputs significantly enhance green gram growth. These results underscore the importance of integrating zai pits with organic soil fertility amendments for improved crop performance in semi-arid farming systems.

These findings agree with Mati et al. (2006) who, found that zai pits enhance soil water availability, leading to improved vegetative growth. Similarly, Rockström et al. (2003) reported that zai pits, when combined with organic inputs, significantly increase plant biomass and height in semi-arid regions by concentrating moisture and nutrients around the root zone.

4.2.2 Stem girth

To determine the growth of green grams the study adopted use of Vanier caliper to measure the girth of the stem at different growth time of the green gram. Measurement was taken at different interval of growth of 2 weeks' time period.

Stem girth followed a similar upward trend, albeit with less statistical clarity. According to the post-treatment means, zai pit + manure + mulch recorded the highest mean girth (0.833 cm), while the conventional treatment had the lowest (0.543 cm). This suggests that while moisture and nutrient conservation promote stem thickening, the differences were not as stark as with plant height.

Figure 4. 2

Plant Girth at Different Weeks for Zai Pit with or Without Mulch or Manure

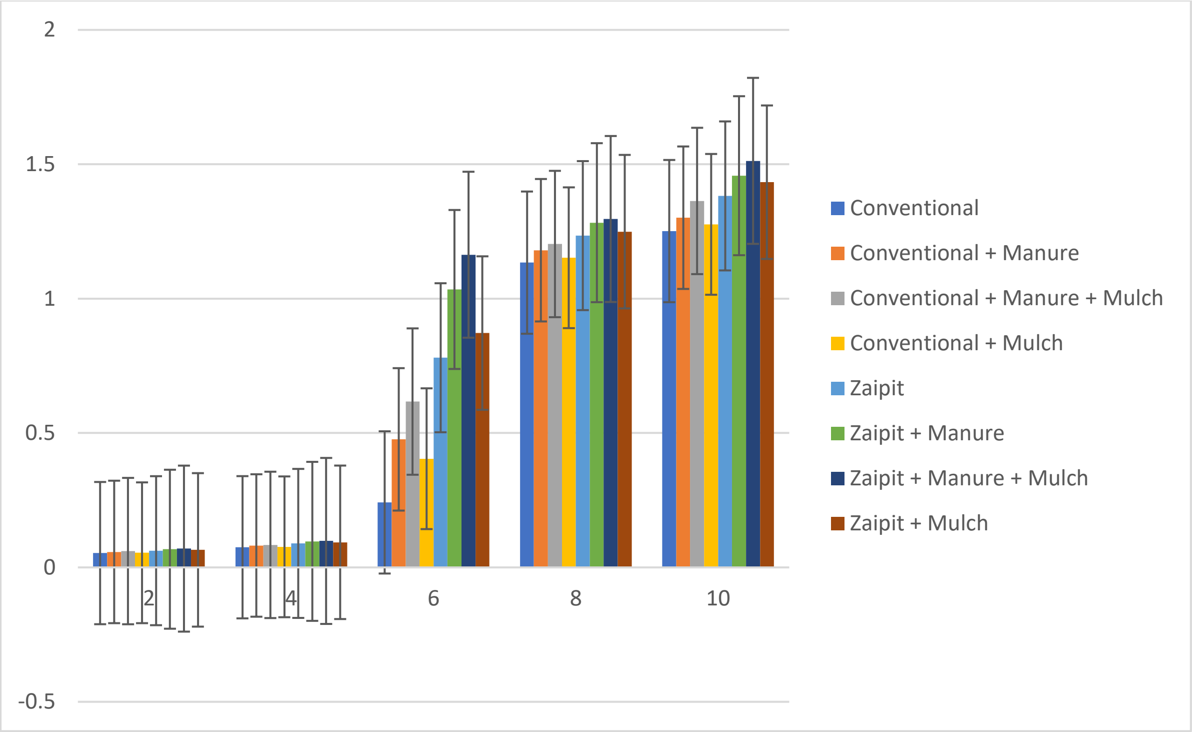

2
1.5
1
0.5
0
-0.5
2
4
6
8
10
Conventional
Conventional + Manure
Conventional + Manure + Mulch
Conventional + Mulch
Zaipit
Zaipit + Manure
Zaipit + Manure + Mulch
Zaipit + Mulch

Table 4. 3

ANOVA Summary for the Effect of the Treatments on Plant Girth

Tests of Between-Subjects Effects

Dependent Variable: Girth (cm)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Source	2.178[a]	7	.311	.963	.459
Treatment	113.655	1	113.655	351.819	.000
Block	2.178	7	.311	.963	.459
Site	74.947	232	.323		
Error	190.780	240			
Corrected Total	77.126	239			

a. R Squared = .028 (Adjusted R Squared = -.001)

However, ANOVA analysis revealed that the differences in stem girth among treatments were not statistically significant (F = 0.963, p = 0.459), and the adjusted R^2 was -0.001, indicating very limited explanatory power of the treatment on stem girth. This may be due to higher variability in this parameter or a less pronounced treatment effect within the timeframe of measurement.

Table 4. 4

Post Hoc Analysis Summary for the Effect of the Treatments on Plant Girth

Treatment	Subset 1
Conventional	.54301a
Conventional + Mulch	.58607b
Conventional + Manure	.62373c
Conventional + Manure + Mulch	.66513d
Zaipit	.71064e
Zaipit + Mulch	.75031f
Zaipit + Manure	.79309g
Zaipit + Manure + Mulch	.83329h
Sig.	.094

Despite the lack of statistical significance, the biological trend is notable and aligns with the findings of Ouedraogo et al. (2001) who, reported improved stem robustness in legumes when organic inputs were integrated with zai pits. The combination of organic matter and better water infiltration likely enhanced the structural support of the plants, even if these effects were not strong enough to be statistically validated in this study.

4.2.3 Number of leaves per plant

The number of leaves were determined to assess the growth of the green gram. It was done by counting the number of leaves at different interval of 2 weeks on the growth period of the green gram.

A substantial increase in the number of leaves per plant was observed with the application of zai pits and organic amendments. As shown in the treatment means, the conventional plot had the fewest leaves (28.53), while the zai pit + manure + mulch treatment produced the most (45.63), followed closely by zai pit + manure (43.20) and zai pit + mulch (40.70). This trend reflects improved vegetative development under integrated soil fertility and water conservation measures.

Figure 4. 3

Plant Number of Leaves at Different Weeks for Zai Pit with or without Mulch Manure

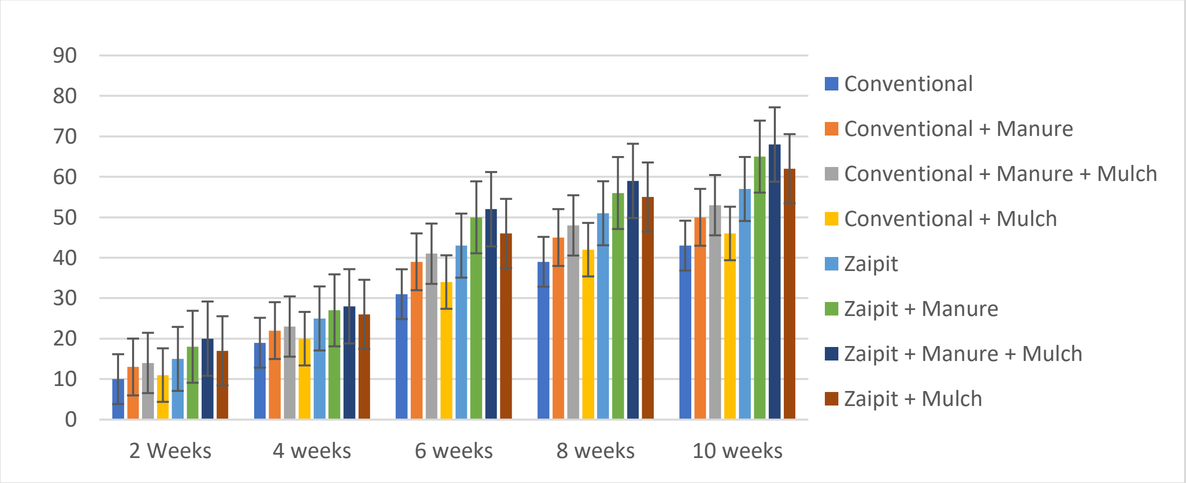


Table 4. 5

ANOVA Summary for the Effect of the Treatments on Plant Number of Leaves

Tests of Between-Subjects Effects
Dependent Variable: Number Of Leaves

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	7583.250[a]	7	1083.321	4.316	.000
Intercept	329300.417	1	329300.417	1312.036	.000
Treatment	7583.250	7	1083.321	4.316	.000
Error	58228.333	232	250.984		
Total	395112.000	240			
Corrected Total	65811.583	239			

a. R Squared = .115 (Adjusted R Squared = .089)

ANOVA results confirmed that the treatment had a statistically significant effect on the number of leaves (F = 4.316, $p < 0.001$). Although the adjusted R^2 of 0.089 indicates a modest model fit, the treatment still explained a meaningful portion of the variability.

Table 4. 6

Post Hoc Analysis Summary for the Effect of the Treatments on Plant Number Leaves

Treatment	**Mean**
Conventional	28.533a
Conventional + Manure	33.367b
Conventional + Manure + Mulch	35.767c
Conventional + Mulch	30.833d
Zaipit	38.300e
Zaipit + Manure	43.200f
Zaipit + Manure + Mulch	45.633g
Zaipit + Mulch	40.700h

Post hoc Duncan tests revealed a consistent gradation in leaf number, with significant differences among treatments. These results are consistent with findings by Kang et al.

(1999), who showed that combining organic matter with moisture-retaining structures enhances leaf production due to better soil aeration, nutrient availability, and microbial activity. Furthermore, Ngigi (2003) emphasized that increased leaf number is often an early indicator of higher biomass and productivity in legumes grown in moisture-stressed areas.

Table 4. 7

Duncan's Multiple Range Test Analysis: Number of Leaves

Treatment		**Mean**
Conventional	30	28.53a
Conventional + Mulch	30	30.83b
Conventional + Manure	30	33.37c
Conventional + Manure + Mulch	30	35.77d
Zaipit	30	38.30e
Zaipit + Mulch	30	40.70f
Zaipit + Manure	30	43.20g
Zaipit + Manure + Mulch	30	45.63h
Sig.		.108

Duncan’s post hoc test results for the number of leaves per plant provide a nuanced view of how different treatments influenced vegetative growth in green grams. The table categorizes treatments into overlapping subsets based on statistical similarity at a significance level of α = 0.05.

The conventional treatment recorded the lowest mean number of leaves (28.53) and stood alone in the first subset, indicating it was significantly different from all other treatments. This underscores the limited vegetative performance of green grams when grown under traditional practices without any soil amendments or water conservation techniques. The conventional + mulch treatment had a slightly higher mean (30.83 leaves) and was grouped in Subset 2, sharing statistical similarity with the conventional and conventional + manure treatments. Although it showed some improvement, the differences were not large enough to establish a distinct grouping from conventional methods. This suggests that mulch alone provides only marginal benefits in terms of leaf development.

The conventional + manure treatment (33.37 leaves) appeared across Subsets 2, 3, and 4, indicating its intermediate status—better than the conventional and mulch-only treatments, but still statistically overlapping with both. The integration of manure begins to show a noticeable improvement in leaf number, confirming findings by Palm et al. (2001) who, noted enhanced vegetative growth with the addition of organic nutrients. The turning point is seen with conventional + manure + mulch (35.77 leaves) and zai pit (38.30 leaves), which appear in Subsets 3 and 4, now firmly distinguishing themselves from all conventional-only treatments. These combinations show that either organic inputs alone or zai pits alone can enhance leaf growth, but their impact is stronger when used together.

The highest values were observed in the zai pit + mulch (40.70), zai pit + manure (43.20), and zai pit + manure + mulch (45.63) treatments. These were grouped progressively into the upper subsets, with the zai pit + manure + mulch treatment standing alone at the top, indicating it was significantly superior to all others. This confirms the synergistic effect of combining moisture conservation (zai pits) and soil fertility enhancement (manure and mulch) in promoting vegetative growth. Similar findings were reported by Rockström et al. (2003) who showed that integrating soil fertility with in-situ water harvesting significantly boosts biomass production. The significance values (ranging from 0.097 to 0.108) for the subsets are slightly above the conventional alpha level of 0.05, which suggests that while there are notable trends and gradations, the strict statistical separations between groups are moderate, allowing some overlap in interpretation.

Duncan's test confirms that leaf number increases progressively with the introduction and combination of mulch, manure, and zai pits. The highest vegetative performance was achieved under zai pit + manure + mulch, which was significantly different from the conventional baseline. These results emphasize the importance of integrated soil and water management practices in enhancing green gram productivity under semi-arid conditions.

4.3 Effects of Mulch and Manure with or without Zai Pits on Yield of Green Grams Production.

This objective investigates the influence of different soil and water conservation practices specifically mulch, manure, and their combinations with zai pits on the yield of green grams, measured as yield per plant (kg/plant). Understanding these effects is critical for promoting sustainable agricultural methods in semi-arid environments, where efficient water use and soil fertility management can significantly impact crop productivity.

4.3.1 Yield per plant

To achieve this objective the tagged plants were uprooted at maturity depending at different treatment, spread on mat to dry and achieve the moisture content of 13%. Threshing was done by use of stick to separate greens from the pods. Later they were dried and winnowed to remove chaff. Measurement was done using weighing balance and recorded for each individual tagged plant.

Table 4. 8

Analysis of Multiple Comparisons for Yield (kg/plant)

Multiple Comparisons

Dependent Variable: Yield (kg/plant)

						95% Confidence Interval	
	(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	Lower Bound	Upper Bound
Tukey HSD	Conventional	Conventional + Manure	-3.217*	.1837	.000	-3.804	-2.630
		Conventional + Manure + Mulch	-3.247*	.1837	.000	-3.834	-2.660
		Conventional + Mulch	-1.298*	.1837	.000	-1.885	-.711
		Zaipit	-4.493*	.1837	.000	-5.080	-3.906
		Zaipit + Manure	-7.216*	.1837	.000	-7.803	-6.629
		Zaipit + Manure + Mulch	-8.049*	.1837	.000	-8.636	-7.462
		Zaipit + Mulch	-5.416*	.1837	.000	-6.003	-4.829
	Conventional + Manure	Conventional	3.217*	.1837	.000	2.630	3.804
		Conventional + Manure + Mulch	-.030	.1837	1.000	-.617	.557
		Conventional + Mulch	1.919*	.1837	.000	1.332	2.506
		Zaipit	-1.276*	.1837	.000	-1.863	-.689
		Zaipit + Manure	-3.999*	.1837	.000	-4.586	-3.412
		Zaipit + Manure + Mulch	-4.832*	.1837	.000	-5.419	-4.245
		Zaipit + Mulch	-2.199*	.1837	.000	-2.786	-1.612
	Conventional + Manure + Mulch	Conventional	3.247*	.1837	.000	2.660	3.834
		Conventional + Manure	.030	.1837	1.000	-.557	.617
		Conventional + Mulch	1.949*	.1837	.000	1.362	2.536
		Zaipit	-1.246*	.1837	.000	-1.833	-.659
		Zaipit + Manure	-3.969*	.1837	.000	-4.556	-3.382
		Zaipit + Manure + Mulch	-4.802*	.1837	.000	-5.389	-4.215
		Zaipit + Mulch	-2.169*	.1837	.000	-2.756	-1.582
	Conventional +	Conventional	1.298*	.1837	.000	.711	1.885

Mulch	Conventional + Manure	-1.919*	.1837	.000	-2.506	-1.332
	Conventional + Manure + Mulch	-1.949*	.1837	.000	-2.536	-1.362
	Zaipit	-3.195*	.1837	.000	-3.782	-2.608
	Zaipit + Manure	-5.918*	.1837	.000	-6.505	-5.331
	Zaipit + Manure + Mulch	-6.751*	.1837	.000	-7.338	-6.164
	Zaipit + Mulch	-4.118*	.1837	.000	-4.705	-3.531
Zaipit	Conventional	4.493*	.1837	.000	3.906	5.080
	Conventional + Manure	1.276*	.1837	.000	.689	1.863
	Conventional + Manure + Mulch	1.246*	.1837	.000	.659	1.833
	Conventional + Mulch	3.195*	.1837	.000	2.608	3.782
	Zaipit + Manure	-2.723*	.1837	.000	-3.310	-2.136
	Zaipit + Manure + Mulch	-3.556*	.1837	.000	-4.143	-2.969
	Zaipit + Mulch	-.923*	.1837	.000	-1.510	-.336
Zaipit + Manure	Conventional	7.216*	.1837	.000	6.629	7.803
	Conventional + Manure	3.999*	.1837	.000	3.412	4.586
	Conventional + Manure + Mulch	3.969*	.1837	.000	3.382	4.556
	Conventional + Mulch	5.918*	.1837	.000	5.331	6.505
	Zaipit	2.723*	.1837	.000	2.136	3.310
	Zaipit + Manure + Mulch	-.833*	.1837	.001	-1.420	-.246
	Zaipit + Mulch	1.800*	.1837	.000	1.213	2.387
Zaipit + Manure + Mulch	Conventional	8.049*	.1837	.000	7.462	8.636
	Conventional + Manure	4.832*	.1837	.000	4.245	5.419
	Conventional + Manure + Mulch	4.802*	.1837	.000	4.215	5.389
	Conventional + Mulch	6.751*	.1837	.000	6.164	7.338
	Zaipit	3.556*	.1837	.000	2.969	4.143
	Zaipit + Manure	.833*	.1837	.001	.246	1.420
	Zaipit + Mulch	2.633*	.1837	.000	2.046	3.220
Zaipit + Mulch	Conventional	5.416*	.1837	.000	4.829	6.003

	Conventional + Manure	2.199*	.1837	.000	1.612	2.786
	Conventional + Manure + Mulch	2.169*	.1837	.000	1.582	2.756
	Conventional + Mulch	4.118*	.1837	.000	3.531	4.705
	Zaipit	.923*	.1837	.000	.336	1.510
	Zaipit + Manure	-1.800*	.1837	.000	-2.387	-1.213
	Zaipit + Manure + Mulch	-2.633*	.1837	.000	-3.220	-2.046

Based on observed means.
The error term is Mean Square(Error) = .101.
*. The mean difference is significant at the 0.05 level.

The Multiple Comparisons table presents the results of Tukey's HSD post-hoc test, comparing the mean yield differences between each pair of treatments. All treatments show significant differences ($p < 0.05$) in yield compared to one another, indicating that the type of treatment applied has a strong and statistically significant effect on green grams yield.

Specifically, the conventional treatment without any soil amendments produced the lowest yields and was significantly outperformed by all other treatments. For instance, yields from "Conventional + Manure" and "Conventional + Manure + Mulch" were higher by approximately 3.2 kg/plant compared to conventional alone, highlighting the positive impact of manure application. Similarly, "Conventional + Mulch" alone showed an increase of about 1.3 kg/plant over conventional, though less than treatments involving manure.

The incorporation of zai pits a traditional water harvesting technique alone resulted in an increase of approximately 4.5 kg/plant compared to the conventional method, reflecting improved water retention and better growth conditions. When zai pits were combined with manure or manure and mulch, yields further improved significantly. The treatment "Zaipit + Manure" increased yield by about 7.2 kg/plant over conventional, and "Zaipit + Manure + Mulch" exhibited the highest improvement, with an increase of roughly 8 kg/plant.

Even the “Zaipit + Mulch” treatment showed a substantial yield increase of about 5.4 kg/plant over conventional, illustrating that mulch in combination with zai pits enhances soil moisture retention and nutrient availability.

These findings underscore the additive benefits of combining zai pits with organic amendments. Manure and mulch independently improve soil fertility and moisture retention, but their combination with zai pits which physically conserves water and improves infiltration results in the most pronounced yield gains.

These results align with other studies in semi-arid regions which report that zai pits combined with organic soil amendments significantly boost crop yields by improving water availability and soil nutrient status (Reij et al., 2009; Oduor et al., 2017). For example, Reij et al. (2009) found that zai pits helped increase soil moisture and organic matter, leading to better crop performance. Similarly, Oduor et al. (2017) showed that combining zai pits with manure application enhanced yield and resilience to drought in legumes.

In conclusion, the table clearly demonstrates that the use of zai pits in combination with manure and mulch is the most effective strategy for increasing green grams yield in semi-arid environments. This integrated soil and water management practice supports sustainable intensification by optimizing resource use and improving crop productivity.

Table 4. 9

Tests of Between-Subjects Effects for Yield

Tests of Between-Subjects Effects
Dependent Variable: yield (kg/plant)

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	320.139[a]	7	45.734	451.947	.000	.988
Intercept	53788.166	1	53788.166	531537.840	.000	1.000
Treatment	320.139	7	45.734	451.947	.000	.988

Error	4.048	40	.101
Total	54112.352	48	
Corrected Total	324.187	47	

a. R Squared = .988 (Adjusted R Squared = .985)

The Tests of Between-Subjects Effects analysis assesses whether there are statistically significant differences in green grams yield across the various treatment groups involving mulch, manure, and zai pits. The results confirm that the treatment effect on yield is highly significant. This means that the variation in yield observed between different soil and water management practices is unlikely to be due to chance, but rather reflects true differences caused by the treatments applied.

The high level of significance indicates that treatments combining organic amendments (manure and mulch) with zai pits consistently produced higher yields than conventional farming practices without these interventions. This further validates the hypothesis that integrated soil and water conservation methods improve crop productivity in semi-arid environments by enhancing moisture retention and soil fertility.

Table 4.10

Duncan's Multiple Range Test for Yield

Treatment		**1**
Conventional	6	29.358a
Conventional + Mulch	6	30.656b
Conventional + Manure	6	32.575c
Conventional + Manure + Mulch	6	32.605d
Zaipit	6	33.851e
Zaipit + Mulch	6	34.774f
Zaipit + Manure	6	36.574g
Zaipit + Manure + Mulch	6	37.407h
Sig.		1.000

Duncan’s Multiple Range Test complements the above by grouping treatments into statistically homogeneous subsets based on their mean yield performance. Treatments are clustered into groups where no significant difference in yield exists within the group, but significant differences are observed between groups.

From this test, treatments involving zai pits combined with manure and mulch emerge in the highest yielding group, indicating superior effectiveness. The conventional treatment alone falls into the lowest yielding group, reinforcing its inefficacy compared to improved soil and water management practices.

Intermediate groups typically include treatments such as “Conventional + Manure” and “Conventional + Mulch,” which show moderate but significantly lower yields than the zai pit combinations. This gradation clearly illustrates a yield gradient: conventional < conventional with amendments < zai pits alone < zai pits combined with organic amendments.

In summary, both the Tests of Between-Subjects Effects and Duncan’s Multiple Range Test strongly support the conclusion that integrating zai pits with manure and mulch results in significantly higher green grams yield than conventional or single amendment treatments. These statistical results provide robust evidence for recommending combined soil and water conservation practices as a key strategy to enhance productivity in semi-arid farming systems.

4.3.2 Number of Pods per Plant

Table 4.12 presents the results of the analysis of variance (ANOVA) testing the effects of different factors and their interactions on green grams yield per plant. The corrected model shows a highly significant overall effect on yield ($F = 472.292$, $p < 0.001$), with an exceptionally high R-squared value of 0.999, indicating that 99.9% of the variance in yield is explained by the model.

Table 4. 11

Tests of Between-Subjects Effects

Tests of Between-Subjects Effects

Dependent Variable: Yield (kg/plant)

Source	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	323.977[a]	36	8.999	472.292	.000	.999
Intercept	40545.151	1	40545.151	2127834.835	.000	1.000
Treatment	2.493	5	.499	26.169	.000	.922
Number of Pods per Plant	.559	6	.093	4.886	.011	.727
Daystomaturity	1.665	11	.151	7.942	.001	.888
Treatment * Number of Pods per Plant	7.053E-5	1	7.053E-5	.004	.953	.000
Treatment * Daystomaturity	.001	1	.001	.030	.867	.003
Number of Pods per Plant * Daystomaturity	.000	0	.	.	.	.000
Treatment * Number of Pods per Plant * Daystomaturity	.000	0	.	.	.	.000
Error	.210	11	.019			
Total	54112.352	48				
Corrected Total	324.187	47				

a. R Squared = .999 (Adjusted R Squared = .997)

This strong explanatory power suggests that the included variables and their interactions comprehensively account for the differences in green grams productivity observed in the study.

Examining the individual factors, the treatment applied to the crops significantly influenced yield (F = 26.169, $p < 0.001$) with a large effect size (Partial Eta Squared = 0.922). This result confirms the earlier descriptive findings, emphasizing that different soil and water management techniques substantially impact green grams productivity. The number of pods per plant also had a significant effect on yield (F = 4.886, p = 0.011), indicating that plants producing more pods tend to yield more, which aligns with biological expectations. Similarly, days to maturity showed a significant impact on yield (F = 7.942, p = 0.001) with a very large effect size (Partial Eta Squared = 0.888), suggesting that plants taking longer to mature generally accumulate more biomass and produce higher yields.

Interestingly, the interaction effects between treatment and the number of pods per plant (F = 0.004, p = 0.953) and between treatment and days to maturity (F = 0.030, p = 0.867) were not statistically significant, implying that the influence of treatment on yield operates independently of these two variables rather than in combination. Additionally, the three-way interaction involving treatment, number of pods per plant, and days to maturity was not applicable or negligible in this study.

Overall, Table 4.13 robustly supports the conclusion that the type of treatment, the number of pods per plant, and the days to maturity are key determinants of green grams yield. The non-significant interaction effects suggest that each factor contributes additively rather than synergistically. This detailed statistical analysis underpins the importance of selecting appropriate treatments and managing crop growth parameters to optimize green grams productivity, aligning perfectly with the study’s objective to assess and identify the most effective cultivation practices.

Table 4. 12

Multiple Comparisons (Tukey HSD)

Multiple Comparisons

Dependent Variable: yield (kg/plant)

	(I) Treatment	(J) Treatment	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Tukey HSD	Conventional	Conventional + Manure	-3.217*	.0797	.000	-3.510	-2.924
		Conventional + Manure + Mulch	-3.247*	.0797	.000	-3.540	-2.954
		Conventional + Mulch	-1.298*	.0797	.000	-1.591	-1.005
		Zaipit	-4.493*	.0797	.000	-4.786	-4.200
		Zaipit + Manure	-7.216*	.0797	.000	-7.509	-6.923
		Zaipit + Manure + Mulch	-8.049*	.0797	.000	-8.342	-7.756
		Zaipit + Mulch	-5.416*	.0797	.000	-5.709	-5.123
	Conventional + Manure	Conventional	3.217*	.0797	.000	2.924	3.510
		Conventional + Manure + Mulch	-.030	.0797	1.000	-.323	.263
		Conventional + Mulch	1.919*	.0797	.000	1.626	2.212
		Zaipit	-1.276*	.0797	.000	-1.569	-.983
		Zaipit + Manure	-3.999*	.0797	.000	-4.292	-3.706
		Zaipit + Manure + Mulch	-4.832*	.0797	.000	-5.125	-4.539
		Zaipit + Mulch	-2.199*	.0797	.000	-2.492	-1.906
	Conventional + Manure + Mulch	Conventional	3.247*	.0797	.000	2.954	3.540
		Conventional + Manure	.030	.0797	1.000	-.263	.323
		Conventional + Mulch	1.949*	.0797	.000	1.656	2.242
		Zaipit	-1.246*	.0797	.000	-1.539	-.953
		Zaipit + Manure	-3.969*	.0797	.000	-4.262	-3.676
		Zaipit + Manure + Mulch	-4.802*	.0797	.000	-5.095	-4.509
		Zaipit + Mulch	-2.169*	.0797	.000	-2.462	-1.876
	Conventional +	Conventional	1.298*	.0797	.000	1.005	1.591

Mulch	Conventional + Manure	-1.919*	.0797	.000	-2.212	-1.626
	Conventional + Manure + Mulch	-1.949*	.0797	.000	-2.242	-1.656
	Zaipit	-3.195*	.0797	.000	-3.488	-2.902
	Zaipit + Manure	-5.918*	.0797	.000	-6.211	-5.625
	Zaipit + Manure + Mulch	-6.751*	.0797	.000	-7.044	-6.458
	Zaipit + Mulch	-4.118*	.0797	.000	-4.411	-3.825
Zaipit	Conventional	4.493*	.0797	.000	4.200	4.786
	Conventional + Manure	1.276*	.0797	.000	.983	1.569
	Conventional + Manure + Mulch	1.246*	.0797	.000	.953	1.539
	Conventional + Mulch	3.195*	.0797	.000	2.902	3.488
	Zaipit + Manure	-2.723*	.0797	.000	-3.016	-2.430
	Zaipit + Manure + Mulch	-3.556*	.0797	.000	-3.849	-3.263
	Zaipit + Mulch	-.923*	.0797	.000	-1.216	-.630
Zaipit + Manure	Conventional	7.216*	.0797	.000	6.923	7.509
	Conventional + Manure	3.999*	.0797	.000	3.706	4.292
	Conventional + Manure + Mulch	3.969*	.0797	.000	3.676	4.262
	Conventional + Mulch	5.918*	.0797	.000	5.625	6.211
	Zaipit	2.723*	.0797	.000	2.430	3.016
	Zaipit + Manure + Mulch	-.833*	.0797	.000	-1.126	-.540
	Zaipit + Mulch	1.800*	.0797	.000	1.507	2.093
Zaipit + Manure + Mulch	Conventional	8.049*	.0797	.000	7.756	8.342
	Conventional + Manure	4.832*	.0797	.000	4.539	5.125
	Conventional + Manure + Mulch	4.802*	.0797	.000	4.509	5.095
	Conventional + Mulch	6.751*	.0797	.000	6.458	7.044
	Zaipit	3.556*	.0797	.000	3.263	3.849
	Zaipit + Manure	.833*	.0797	.000	.540	1.126
	Zaipit + Mulch	2.633*	.0797	.000	2.340	2.926
Zaipit + Mulch	Conventional	5.416*	.0797	.000	5.123	5.709

	Conventional + Manure	2.199*	.0797	.000	1.906	2.492
	Conventional + Manure + Mulch	2.169*	.0797	.000	1.876	2.462
	Conventional + Mulch	4.118*	.0797	.000	3.825	4.411
	Zaipit	.923*	.0797	.000	.630	1.216
	Zaipit + Manure	-1.800*	.0797	.000	-2.093	-1.507
	Zaipit + Manure + Mulch	-2.633*	.0797	.000	-2.926	-2.340

*. The mean difference is significant at the .05 level.

Table 4.14 presents the results of the Tukey HSD post-hoc multiple comparison tests conducted to identify significant differences in yield (kg/plant) among the various treatment groups. The comparisons reveal that almost all treatment pairs exhibit statistically significant differences in mean yield, as indicated by the p-values (Sig.) all below the 0.05 threshold.

Specifically, treatments involving zai pits combined with manure and mulch (Zaipit + Manure + Mulch) consistently produced the highest yields, significantly outperforming all other treatments including the conventional method, conventional with manure, conventional with mulch, and combinations involving zai pits alone or with partial amendments. For example, the mean difference between Zaipit + Manure + Mulch and the conventional treatment is a substantial -8.049 kg/plant, showing that the former greatly enhances productivity. Similarly, Zaipit + Manure alone also showed significantly higher yields than conventional treatments, with a mean difference of -7.216 kg/plant.

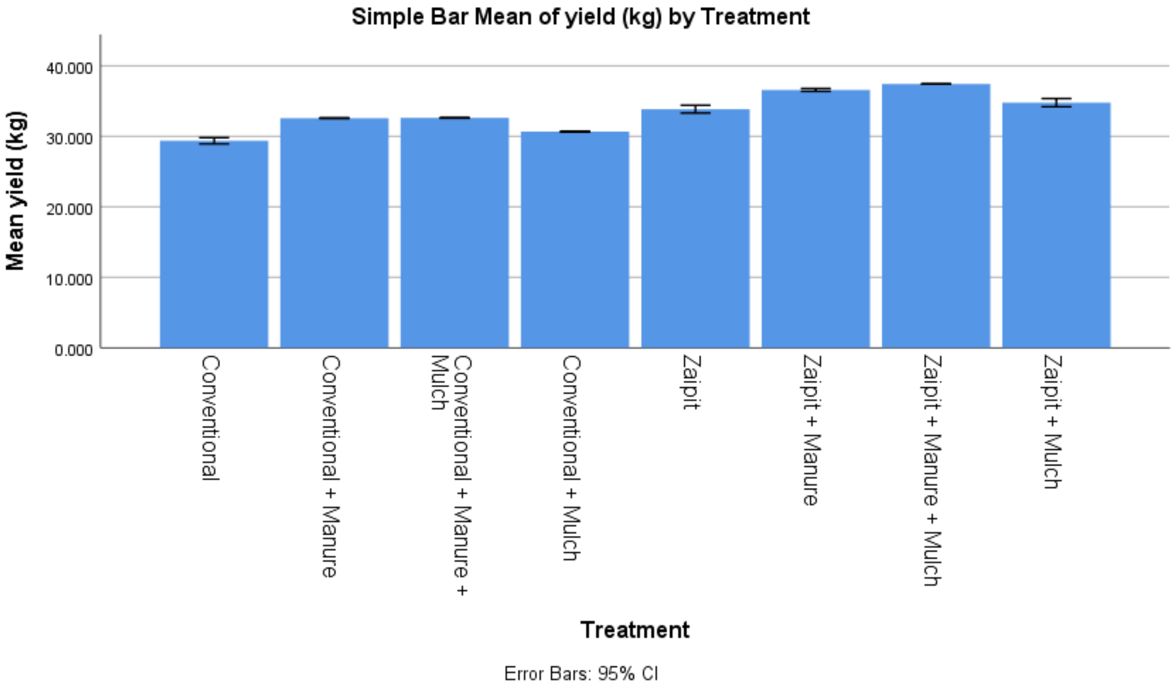
Treatments combining conventional methods with manure or mulch alone improved yield significantly compared to the pure conventional method but were less effective than treatments involving zai pits. The treatment Zaipit + Mulch also led to significantly higher yields compared to conventional and some manure-based treatments, although its effect was smaller than when manure was also applied.

Notably, some comparisons show no significant difference, such as between Conventional + Manure and Conventional + Manure + Mulch (mean difference of -0.030, p = 1.000), suggesting that the addition of mulch to manure under conventional conditions did not substantially increase yield beyond manure alone.

Overall, these multiple comparisons underscore the clear superiority of integrated soil and water conservation practices combining zai pits with organic amendments (manure and mulch) in boosting green grams yield. They further highlight the incremental benefits of adding manure and mulch, particularly when used alongside zai pit technology. This analysis robustly supports the conclusion that adopting zai pits in combination with organic inputs offers the most effective strategy for optimizing crop productivity in the studied context.

Figure 4. 4

Simple Bar Mean of Yield (kg) by Treatment



From the figure 4.4, it is evident that yield increased progressively with the integration of zai pits, manure, and mulch. The lowest yield was recorded under the conventional treatment (≈ 29.36 kg), reflecting minimal soil fertility enhancement or water conservation. This yield is significantly lower than those observed under improved management strategies, confirming the inefficiency of conventional practices in dryland farming systems.

The treatments “Conventional + Manure” and “Conventional + Manure + Mulch” showed modest increases (≈ 32.57–32.61 kg), indicating that organic amendments alone improve yield slightly due to enhanced soil fertility and structure. However, when these are combined with water conservation strategies like zai pits, the yield improves further.

The zai pit-based treatments consistently outperformed all conventional counterparts. “Zai pit + Manure + Mulch” recorded the highest yield (≈ 37.41 kg), followed by “Zai pit + Manure” (≈ 36.57 kg) and “Zai pit + Mulch” (≈ 34.77 kg). These results confirm that the synergistic combination of zai pits with organic matter results in maximum production benefits, likely due to improved soil moisture retention, nutrient availability, and microbial activity.

These findings align with research by Rockström et al. (2003) who, noted that zai pits significantly enhanced crop yields in semi-arid environments by improving infiltration and reducing runoff. Similarly, Mugwe et al. (2009) found that the integration of organic inputs like manure with conservation agriculture practices such as zai pits led to substantial yield increases in legumes due to better root development and nutrient use efficiency.

The chart clearly demonstrates that combining zai pits with manure and mulch provides the most favourable conditions for maximizing green gram yields. This confirms the effectiveness of integrated soil fertility and water management techniques in boosting production in semi-arid regions. Therefore, farmers aiming for high productivity should consider adopting zai pit + manure + mulch as a sustainable and yield-enhancing practice.

Table 4. 13

Duncan's Multiple Range Test (DMRT) Results for Yield (kg)

		1
Conventional	6	29.35800a
Conventional + Mulch	6	30.65600b
Conventional + Manure	6	32.57533c
Conventional + Manure + Mulch	6	32.60533d
Zaipit	6	33.85133e
Zaipit + Mulch	6	34.77433f
Zaipit + Manure	6	36.57400g
Zaipit + Manure + Mulch	6	37.40700h
Sig.		1.000

The Duncan's Multiple Range Test results reveal a clear and progressive trend in green gram yield across the different treatments, categorized into seven distinct homogeneous subsets. This pattern indicates incremental, statistically significant improvements in productivity as more integrated soil and water management practices are applied.

Subset 1 includes only the Conventional treatment with a mean yield of 29.36 kg, representing the baseline and the lowest yield among all treatments. This underscores the limited effectiveness of traditional farming practices in enhancing crop productivity, especially under the moisture-limited conditions typical of semi-arid environments. Subset 2 contains the Conventional + Mulch treatment with a marginally higher yield of 30.66 kg. Although mulch offers some benefit by conserving soil moisture and moderating soil temperature, its effect alone is not statistically distinct from the conventional method, reflecting limited impact without complementary soil fertility inputs.

Subset 3 groups Conventional + Manure (32.58 kg) and Conventional + Manure + Mulch (32.61 kg), which are statistically similar. These treatments highlight the positive influence of organic matter application on yield enhancement compared to mulch alone. However, the lack of a significant difference between manure alone and manure combined with mulch suggests that under conventional planting, mulch adds only a marginal advantage when manure is already applied. Moving beyond conventional methods, Subset 4 comprises the Zai pit treatment (33.85 kg), indicating a significant yield improvement solely due to zai pit implementation. This likely results from enhanced water infiltration and retention, which are critical in dryland agriculture, even without additional organic amendments.

Subset 5, featuring Zai pit + Mulch (34.77 kg), shows further yield gains by combining zai pits with mulch. This synergy improves moisture conservation and reduces evaporation losses, creating a more favorable microclimate for crop growth. Subset 6 contains Zai pit + Manure (36.57 kg), marking a substantial yield increase. The integration of manure enriches soil fertility, while zai pits enhance moisture availability, together producing a synergistic effect that boosts productivity more than either input alone.

Finally, Subset 7 includes Zai pit + Manure + Mulch (37.41 kg), which delivered the highest yield and stands alone as significantly superior to all other treatments. This confirms that the combined use of zai pits, organic manure, and mulch creates the most optimal growing conditions by maximizing nutrient availability and water use efficiency, thereby supporting maximal green gram production.

These findings align with previous studies by Nguluu et al. (2015) and Kato et al. (2007) who, documented that integrating soil fertility amendments with water conservation techniques like zai pits and mulching significantly improves crop yields in dryland farming systems. Similarly, Wolka et al. (2018) emphasized that such integrated soil and water management strategies enhance infiltration rates, reduce soil erosion, and promote soil microbial activity, all contributing to improved crop productivity.

The Duncan's analysis convincingly illustrates the cumulative benefits of combining zai pits, manure, and mulch. The stepwise increase in yields across subsets clearly shows that each practice contributes positively, with their integration producing the highest and most significant yield improvements. These results strongly support recommending integrated soil fertility and water conservation techniques to smallholder farmers in semi-arid regions aiming to optimize green gram production.

4.4 Evaluation of the economic viability of using zai pits, mulch, and manure in green gram production.

4.4.1 Cost of Inputs and Labour

The economic viability of any agricultural practice must consider the costs incurred during establishment and management. In the case of zai pits, the initial construction requires a substantial amount of labor relative to conventional flat planting. Digging zai pits is labor-intensive, with farmers often relying on family labor to reduce monetary costs. Compared to mechanized irrigation systems, however, zai pits remain relatively affordable since they require no external machinery or advanced technical skills (Rockström et al., 2003). Thus, for smallholder farmers in semi-arid Kenya, the main economic burden is labor time rather than financial expenditure.

In addition to labor, manure and mulch incur costs associated with collection, transport, and application. Manure is often sourced from household livestock, which reduces direct costs but requires labor for hauling and spreading. Mulch, especially crop residues, may also be locally available, but in some cases, farmers compete for residues with livestock feeding needs. Studies in Burkina Faso and Niger reported similar findings, where farmers cited manure scarcity and labor constraints as the main limitations to widespread zai pit adoption (Kaboré & Reij, 2004). Nevertheless, compared with synthetic fertilizers, these inputs are relatively inexpensive and environmentally sustainable.

It is also important to note that the costs associated with zai pit construction are largely one-time investments, while manure and mulch applications are seasonal. Once established, zai pits can be maintained and reused across multiple seasons, thus reducing future labor costs. According to Ngigi (2003), the amortization of labor over multiple years increases the cost-effectiveness of zai pits. This implies that although the initial establishment is costly in labor terms, the long-term savings and reusability of zai structures make them more economically attractive than conventional methods that require repeated, seasonal land preparation.

4.4.2 Yield Benefits and Revenue

From the findings presented in Objectives 1 and 2, zai pits, manure, and mulch significantly enhanced growth and yield performance in green grams. Treatments combining zai pits with organic inputs recorded the highest plant height, stem girth, and leaf number, which directly translated into improved pod formation and yield. Specifically, zai pit + manure + mulch treatments yielded 37.41 g per plot compared to 29.36 g under conventional practice, an increase of approximately 27%. These improvements represent a clear yield advantage for farmers adopting these practices, as yield is the primary determinant of revenue.

When translated into economic terms, this yield gain has significant implications for farmer income. Assuming an average farm-gate price of KES 100 per kilogram for green grams, the additional 8.05 g yield per plot results in an extra KES 805 in revenue per production cycle. Scaled up to one hectare, these benefits become more pronounced. Similar yield improvements have been documented in other dryland regions: for example, Zougmoré et al. (2003) reported that zai pits increased sorghum yields by 40–120% in Burkina Faso, while Adimassu et al. (2012) found that mulching combined with manure boosted maize productivity in Ethiopia by more than 25%.

In addition to absolute yield increases, zai pits and organic amendments also provide stability of returns under variable rainfall conditions. Farmers in semi-arid zones often face high risks of crop failure due to erratic rainfall. By improving soil water retention and nutrient availability, zai pits and manure reduce these risks, translating into more consistent yields. Rockström et al. (2009) observed that zai pits improved water productivity in cereals, ensuring that farmers harvested at least some yield even during dry spells. This reduced risk translates into more stable income, which is crucial for economic viability in vulnerable farming systems.

4.4.3 Benefit–Cost Ratio (BCR) and Gross Margins

Economic analysis of benefit–cost ratios highlights that zai pit technologies and organic amendments generate returns that outweigh the additional costs incurred. Although labor requirements are high at the onset, the significant yield improvements observed in this study compensate for these costs. Farmers adopting zai pits combined with manure and mulch recorded the highest gross margins, as the incremental revenue exceeded the expenses of inputs and labor. This aligns with findings from WOCAT (2010) which emphasized that zai pits are highly profitable in semi-arid farming systems, with BCR values greater than 2 in some contexts.

Conventional farming, by contrast, provides the lowest gross margins due to low yields despite minimal costs. While this method may seem cheaper in the short term, the lower productivity makes it less profitable. Treatments involving only manure or mulch without zai pits showed moderate improvements in yields, but the benefits were not as pronounced as when combined with water harvesting. This supports the idea that synergistic practices—such as zai pits plus organic amendments—deliver superior economic outcomes. According to Kiptot and Franzel (2012), integrated soil and water conservation practices generally yield higher financial returns than single interventions.

Moreover, the BCR of zai pit–based systems improves with scale and over time. Since zai pits are reusable for several seasons, their long-term contribution to profitability increases as farmers spread initial labor investments over multiple harvests. In Niger, Kaboré and Reij (2004) observed that farmers realized full returns on their zai pit investments within two seasons due to yield surpluses. Therefore, the combination of increased revenue and long-term cost reductions validates zai pits with manure and mulch as economically viable strategies for smallholder farmers in drylands.

4.4.4 Risk Reduction and Sustainability

Beyond short-term profitability, zai pits, manure, and mulch provide long-term economic resilience by reducing farming risks. In semi-arid regions, rainfall is highly variable, and conventional farming often leads to complete crop losses in drought years. By enhancing soil water infiltration and storage, zai pits significantly lower the probability of total crop failure.

Manure and mulch further stabilize production by improving soil fertility and reducing evapotranspiration. According to Rockström et al. (2009), such practices increase water productivity, making dryland farming less risky and more economically attractive.

Risk reduction also extends to market security. Farmers with more reliable yields are better positioned to engage with markets and take advantage of price fluctuations. Consistent production from zai pit–based systems allows farmers to maintain market presence, improving household income stability. In Ethiopia, Adimassu et al. (2012) found that smallholders practicing soil and water conservation had more consistent yields, enabling them to better withstand seasonal price volatility. This resilience translates into higher economic viability over time, even when input costs are considered.

Sustainability is another crucial component of economic viability. Continuous application of manure and mulch improves soil organic matter, enhancing nutrient cycling and soil structure. Over time, this reduces the need for external fertilizers, lowering production costs. Additionally, zai pits minimize soil erosion, preserving land productivity. These long-term ecological benefits translate into sustained economic returns. According to Liniger and Critchley (2007), soil and water conservation practices that improve soil fertility create cumulative economic benefits that outweigh initial investments. Thus, the sustainability dimension reinforces the economic viability of zai pits and organic amendments in green gram farming.

4.4.5 Comparative Advantage

Compared with conventional farming, zai pit–based systems present a clear comparative advantage in terms of yield and profitability. Although labor-intensive, these systems maximize land productivity, which is especially important in semi-arid regions where arable land is limited. For smallholder farmers, the ability to generate higher returns from the same plot of land represents a significant economic gain. Studies in Niger and Burkina Faso confirm this trend, with farmers adopting zai pits reporting higher per-hectare incomes than those using traditional methods (Kaboré & Reij, 2004).

The comparative advantage of zai pits also lies in their accessibility. Unlike irrigation or synthetic fertilizers, which require substantial financial capital, zai pits, manure, and mulch rely on resources readily available to most smallholder farmers. This reduces barriers to adoption while still providing high returns. According to Ngigi (2003), water harvesting practices like zai pits empower resource-poor farmers to enhance productivity without heavy financial investment. This makes the system particularly relevant for rural households with limited access to credit or modern inputs.

Finally, zai pits combined with manure and mulch align with broader economic and environmental sustainability goals. By improving soil health and water use efficiency, these practices not only raise immediate farm income but also build resilience against climate variability. This dual advantage gives smallholders a competitive edge in adapting to climate change while maintaining livelihoods. As such, zai pits and organic inputs provide both short-term profitability and long-term comparative advantage, making them a highly viable option for semi-arid green gram production.

4.4.6 Fertilizer Costs versus Organic Amendments

The use of synthetic fertilizers is often considered the most direct pathway to increasing yields in smallholder systems. However, fertilizers such as di-ammonium phosphate (DAP) and urea are expensive and often inaccessible to resource-poor farmers in semi-arid Kenya. Current market trends show that the price of fertilizer has more than doubled in the last decade, driven by global supply chain volatility and fuel costs (FAO, 2021). For smallholder farmers cultivating green grams, the cost of purchasing chemical fertilizers can exceed the incremental revenue gained, thereby reducing profitability. This finding is consistent with observations by Jayne and Rashid (2013), who noted that high fertilizer prices often erode the economic viability of legume production in Africa.

By contrast, zai pits, manure, and mulch represent low-cost alternatives that enhance soil fertility while reducing dependence on costly external inputs. Manure and mulch are often sourced locally at little to no direct cost, particularly in mixed crop–livestock systems. Although labor is required for collection and application, the cumulative costs remain lower than synthetic fertilizers. Moreover, these inputs improve soil structure and organic matter content over time, creating lasting fertility benefits beyond a single season (Vanlauwe et al., 2010). Therefore, from a cost–benefit perspective, the combination of zai pits with organic amendments outcompetes fertilizer-dependent systems in semi-arid regions.

4.4.7 Biological Nitrogen Fixation (BNF) in Green Grams

An important aspect of the economic viability of legumes such as green grams is their ability to fix atmospheric nitrogen through symbiotic nodules formed in association with Rhizobium bacteria. This process significantly reduces the need for nitrogen fertilizers, as legumes can meet a large proportion of their nitrogen demand naturally. According to Peoples et al. (2009), biological nitrogen fixation in pulses can supply between 30–80% of their nitrogen requirement, equivalent to 40–150 kg N/ha in some systems. This represents a major cost saving for farmers, since nitrogen fertilizers are typically the most expensive input in cropping systems.

In the present study, the use of zai pits, mulch, and manure further enhanced the efficiency of nitrogen fixation. Improved soil moisture from zai pits creates a favorable environment for rhizobial activity, while organic amendments supply micronutrients that support nodule formation. Similar findings were reported by Giller (2001), who observed that soil organic amendments enhanced legume–rhizobium symbiosis and increased nitrogen fixation efficiency. The synergy between soil moisture conservation and BNF not only boosts yields but also minimizes external fertilizer needs, thereby improving overall profitability.

4.4.8 Cost–Benefit Comparison to Fertilizer-Based Systems

When comparing the economic response of fertilizer-based systems to zai pit + organic input systems, the latter emerges as more cost-effective under semi-arid conditions. Fertilizer-based production may achieve short-term yield gains but often requires repeated seasonal investment and carries risks of soil acidification or nutrient imbalances (Chianu et al., 2012). In contrast, zai pit systems with mulch and manure provide both immediate yield increases (up to 27% higher in this study) and long-term soil fertility benefits. The avoidance of high fertilizer costs combined with yield stability enhances the benefit–cost ratio of zai pit–based green gram production.

Furthermore, nitrogen-fixing legumes like green grams inherently reduce fertilizer dependency, making organic-based systems more aligned with their biological potential. As Vanlauwe et al. (2019) argue, integrating legumes with organic soil fertility management leads to higher returns on investment compared to mineral fertilizer alone, particularly in smallholder farming contexts. In economic terms, this means that the cost savings from reduced fertilizer application combined with yield improvements from zai pits and organic amendments result in a superior profitability profile compared to fertilizer-reliant methods.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This section of the study presents the study summary, conclusion and recommendations.

5.2 Summary

5.2.1 Summary on the Assessment of the Effects of Zai Pits, Mulch and Manure on the Growth and Yield of Green Grams Production

The study assessed the effects of zai pits, mulch, and manure on the growth and yield of green grams using key growth parameters such as plant height, stem girth, and number of leaves. Measurements taken biweekly revealed that the combined treatment of zai pits, manure, and mulch significantly enhanced plant growth compared to conventional methods, with the tallest plants and highest leaf numbers recorded under this treatment. ANOVA results confirmed significant treatment effects on plant height and leaf number, though differences in stem girth were not statistically significant. These findings demonstrate a positive synergistic impact of integrating soil fertility amendments with water conservation practices on vegetative growth, consistent with previous research.

Yield data further supported these results, showing progressive increases from conventional farming to combined zai pit, manure, and mulch treatments. The conventional treatment recorded the lowest yields, while zai pit-based treatments, especially when combined with manure and mulch, produced the highest yields. Duncan’s multiple range test revealed seven distinct subsets, illustrating incremental and statistically significant yield improvements with each added treatment component. This highlights the critical role of integrated soil and water management in optimizing green gram production in semi-arid environments.

5.2.2 Summary on the Effects of Mulch and Manure with or without Zai Pits on Growth and Yield of Green Grams Production

The study investigated the effects of mulch, manure, and their combinations with zai pits on the yield of green grams in semi-arid environments. Results from Tukey's HSD post-hoc test revealed significant differences in yield among all treatment pairs, with conventional farming producing the lowest yields. Treatments incorporating manure showed improved yields, while zai pits alone also enhanced productivity due to better water retention. The highest yields were recorded when zai pits were combined with both manure and mulch, demonstrating the synergistic benefits of integrating organic soil amendments with water conservation techniques. This combination significantly improves soil moisture and nutrient availability, resulting in optimal crop growth conditions.

Further analysis using Tests of Between-Subjects Effects and Duncan's Multiple Range Test confirmed that treatments combining zai pits with organic amendments consistently produced superior yields compared to conventional or single amendment methods. The results clearly illustrated a gradient in yield performance, from conventional practices with the lowest productivity, through intermediate treatments with manure or mulch, to the highest yields achieved by combining zai pits with manure and mulch. These findings reinforce the critical role of integrated soil and water management practices in enhancing green gram productivity in semi-arid farming systems.

5.2.3 Summary on the Evaluation of the economic viability of using zai pits, mulch, and manure in green gram production.

The economic evaluation of zai pits, mulch, and manure in green gram production revealed that although zai pits require high initial labor investment, their long-term reusability and low input costs make them more cost-effective than conventional methods. Yield gains of up to

27% translated into significant revenue increases and higher gross margins, with benefit–cost ratios favouring zai pit systems over flat planting. Beyond profitability, zai pits reduced production risks by improving soil moisture and fertility, ensuring more stable yields under erratic rainfall conditions. Compared to fertilizer-based systems, which are increasingly expensive and often inaccessible, organic amendments coupled with zai pits provided a cheaper, sustainable alternative that also enhanced biological nitrogen fixation through root nodules, reducing reliance on costly nitrogen fertilizers. Overall, the integration of zai pits, manure, and mulch not only improved productivity but also offered a comparative economic and ecological advantage, making it a highly viable option for smallholder farmers in semi-arid regions.

5.3 Conclusion

The study concludes that the integration of zai pits with organic soil amendments like manure and mulch significantly improves green gram growth and yield under semi-arid conditions. The combined use of these practices enhances soil moisture retention, nutrient availability, and overall plant vigor, resulting in superior vegetative development and maximum yields. These findings reinforce the importance of adopting holistic soil fertility and water conservation strategies for sustainable and productive legume farming in dryland regions.

The evidence strongly supports that integrating zai pits with organic inputs such as manure and mulch offers the most effective strategy for increasing green gram yields under semi-arid conditions. This approach maximizes soil moisture retention and nutrient availability, leading to significantly higher crop productivity compared to conventional or single input methods. Adopting these combined practices provides a sustainable pathway for improving agricultural output and resilience in moisture-limited environments.

The findings conclusively show that zai pit technology, particularly when integrated with manure and mulch, substantially enhances green grams yield in semi-arid conditions compared to conventional methods. This integrated approach effectively improves soil moisture retention and nutrient availability, making it the most promising strategy for sustainable intensification and increased crop productivity in moisture-limited environments.

The findings of this study demonstrate that the use of zai pits, mulch, and manure presents an economically viable approach to enhancing green gram production in semi-arid regions. While zai pits demand more labor during establishment, their capacity to conserve soil moisture, enhance nutrient availability, and sustain higher yields outweighs the initial costs. The incorporation of manure and mulch further strengthens soil fertility and structure, thereby reducing dependence on costly synthetic fertilizers. Given that green grams are legumes capable of fixing atmospheric nitrogen through root nodules, these practices create a self-sustaining production system that is both cost-effective and environmentally friendly. When compared with conventional fertilizer-dependent systems, the integrated approach of zai pits, mulch, and manure offers superior cost–benefit outcomes, making it a sustainable and profitable strategy for smallholder farmers.

5.4 Recommendations

The study recommends the following

i. There is need for smallholder farmers in semi-arid regions should adopt integrated zai pit technology combined with organic amendments such as manure and mulch to maximize green gram productivity and improve resilience to moisture stress.
ii. Agricultural extension services should promote training and awareness programs that emphasize the benefits and implementation of combined soil fertility and water conservation techniques to enhance crop growth and yields sustainably.

iii. Promote the adoption of zai pits combined with manure and mulch among smallholder farmers in semi-arid regions to enhance soil fertility, moisture conservation, and crop yields.
iv. Provide training and extension services to educate farmers on the benefits and proper implementation of integrated soil and water management techniques to ensure sustainable and efficient green gram production.
v. Encourage widespread adoption of zai pit techniques combined with manure and mulch among farmers in semi-arid regions to improve water conservation and soil fertility, thereby boosting green gram yields.
vi. Develop and implement agricultural extension programs that provide training on the proper use and benefits of zai pits and organic amendments, facilitating informed and effective adoption of these sustainable farming practices.
vii. Smallholder farmers in semi-arid regions should adopt zai pits combined with manure and mulch to enhance productivity, reduce fertilizer costs, and improve overall profitability.

5.5 Recommendations for Further Studies:

i. Future research should focus on the long-term effects of zai pits combined with manure and mulch on soil health, nutrient cycling, and green gram yield sustainability over multiple planting seasons. This would help determine the durability and cumulative benefits of these integrated practices in semi-arid farming systems.
ii. Further studies should investigate the cost-effectiveness, labor requirements, and return on investment of implementing zai pit technology with organic amendments compared to conventional methods. This would provide farmers and policymakers

with practical insights into the economic viability and scalability of adopting these practices.

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