DETERMINATION OF THE EFFECTS OF CROP ROTATION, WATER HARVESTING AND SOIL FERTILITY MANAGEMENT ON NITROGEN AND WATER USE EFFICIENCY OF WHEAT IN NJORO SUB-COUNTY, KENYA

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and to the best of my knowledge has not been presented at any other institution known to me for the award of any degree.

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Recommendation

This thesis has been submitted for examination with our approval as University supervisors.

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DEDICATION

This thesis is dedicated to my wife Sylvia and my son Collins and daughters Lorine, Grace and Marylynn.

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ABSTRACT

Wheat production in Njoro Sub – County, Nakuru, Kenya is constrained by many problems including low soil moisture and nitrogen (N) levels resulting in low wheat yields. Thus, the experiments to determine the effects of water harvesting (WH), crop rotation (CR) and soil fertility management (SFM) on N use efficiency (NUE), water use efficiency (WUE) and performance of wheat were conducted at Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro between 2014 and 2016. Three factors were evaluated in a randomized complete block design (RCBD) with split-split plot replicated three times. These factors included (i) two levels of WH (main plot) (flat bed and tie ridge) (ii) four levels of CR (sub-plot) with different crop sequence each year [(CR1= wheat (*Triticum aestivum* – lablab (*Lablab purpureus*) – *T. aestivum)*; CR 2= *T. aestivum* –green pea (*Pisum sativum*) - *T. aestivum*); CR 3 =*T. aestivum* –potato (*Solanum tuberosum*) - *T. aestivum*); CR 4 = Continuous wheat for 3 years)] and (iii) six levels of SFM (sub-sub-plot) [FYM at 5 t ha^{-1}; green manure (*Leucaena trichandra*) at 2.5 t ha^{-1}; calcium ammonium nitrate (CAN) fertilizer at 25, 50 and 75 kg N ha^{-1}; and untreated control]. Data was subjected to analysis of variance (ANOVA) using Genstat and mean separation was performed using least significance difference (Lsd) at 5% level of significance. Results showed that NUE and NU_pE was improved when (*T. aestivum*) was preceded by either *L.purpureus* or *P. sativum* in the CR treatments. Soil fertility management (SFM) significantly ($p < 0.05$) influenced NUE, NU_tE, NU_pE as well as WUE as well as yield and biomass. Two – way (CR x SFM) interactions significantly ($p < 0.05$) affected NUE, NU_tE, NU_pE as well as WUE and yield of wheat. Green manure (GM) on plots previously occupied by a legume (*L. purpureus*) or *P. sativum*) increased NUE by 46% while NU_pE of wheat was improved by 36% when wheat was grown with the lowest rate (25 kg N ha^{-1}) of inorganic fertilizer on plots that were previously on green pea. The lowest rate of N (25 kg N ha^{-1}) after *L. purpureus* or *P. sativum* improved NU_tE by 14 and 12%, respectively. However, a three – way (WH x CR x SFM) interaction showed significant ($p < 0.001$) effect on WUE and grain yield. Wheat planted with FYM at 5 tonnes ha^{-1} on flat beds (WH1) previously occupied by *L. purpureus* significantly ($p < 0.05$) increased WUE and grain yield 25% and 31%, respectively. In order to maximize NUE and its attributes *L. purpureus* or *P. sativum* may be used as precursor crops to *T. aestivum* in the CR systems. Organic fertilizer (FYM or GM) positively influenced NUE and its attributes, WUE and grain yield of wheat. This could replace inorganic sources of N if a legume pre-crop to *T. aestivum*.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEZ	Agro-Ecological Zones
ANOVA	Analysis of Variance
CAN	Calcium Ammonium Nitrate
CC	Climate Change
CO	Carbon Monoxide
ERS	Economic Recovery Strategy
FAO	Food and Agriculture Organization
GAPs	Good Agricultural Practices
GDP	Gross Domestic Production
GHG	Greenhouse Gases
GoK	Government of Kenya
IPCC	Intergovernmental Panel on Climate Change
KARI	Kenya Agricultural Research Institute
KALRO	Kenya Agricultural and Livestock Research Organization
LER	Land Equivalent Ratio
NCCRS	National Climate Change Response Strategy
NPBRC	National Plant Breeding Research Centre
NUE	Nitrogen Use Efficiency
SFM	Soil Fertility Management
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TDR	Time Domain Reflectance
WUE	Water Use Efficiency
NU_pE	Nitrogen Uptake Efficiency
NU_tE	Nitrogen Utilization Efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Worldwide, wheat (*Tritcum aestivum,* L) is grown on more land area than any other cereal crops such as rice and maize (Igrejas & Branlard, 2020) with a production of 750 million tonnes (MT) on about 220 million hectares (MHa) in 2017 (Tadesse *et al.,* 2019). "Sub-Sahara Africa (SSA) produced a total of 7.5 MT on a total area of 2.9 MHa in 2017 accounting for 40 and 1.4 per cent of the wheat production in Africa and at global levels, respectively" (FAO, 2017). Kenya is the fourth highest wheat producer in the SSA after Ethiopia, South Africa and Sudan and produced 270 thousand tonnes (MT) in 2020 on about 150 thousand hectares (MHa) (Xinhuanet, 2021).

Both biotic (yellow rust, stem and leaf rust) and abiotic (declining soil fertility, copper deficiency, and soil acidity) stresses affect wheat productivity in Kenya (Kamwaga *et al.,* 2016). In order to combat low soil fertility in Kenya's wheat-growing regions, a range of inorganic fertilizers comprising Nitrogen, Phosphorous, and Potassium (NPK) are widely utilized. The amounts and types of NPK fertilizers used vary depending on the crops cultivated.

Nitrogen (N) is the most important nutrient for cereal production, however, the water resource must be used efficiently in order for the applied or inherent N to benefit the cereal production system (Fageria & Baligar, 2005). Thus, N and water use must be considered when millions of tonnes of cereals are produced each year. While high fertilizer use affects agricultural productivity in developed countries, where more N fertilizer use is associated with higher yields, the same trend cannot be anticipated in developing countries due to a variety of production restrictions (Beatty *et al.,* 2010; Bingham *et al.,* 2012). Kenya, for example, imported roughly 450,000 tonnes of various fertilizer typess in 2015 alone (Africafertilizer.org report, 2017), with N-based fertilizer accounting for about 30% of this total. Despite the fact that vast volumes of N fertilizers have been used around the world, crop recovery or efficient use of N fertilizers on arable lands has remained relatively low, ranging from 25% to 50% of the applied N. (Doberrmam, 2003; Chien *et al.,* 2016). Low NUE results in a number of negative consequences, including environmental contamination, economic inefficiency, and inefficient resource utilization, indicating a pressing need to improve fertilizer NUE (Anas *et al.,* 2020). Apart from the increased use of N, farmers are concerned about the quick rise in fertilizer prices.In contrast to the industrialized world, the SSA uses extremely little nitrogen fertilizer (an average of 4 kg N ha^{-1}), hence NUE estimations have been greatly overstated (Varvel & Peterson, 1991). Furthermore, this is a misrepresentation because nutrient mining, particularly N mining, has occurred in practically all regions where cereals are grown in SSA, depleting the natural soil resource (Edmonds *et al.,* 2009). Because of the low levels of nitrogen utilization in the SSA region, high NUE values of over 100% have been observed, showing a considerably more serious and potentially detrimental condition for cereal production in the region (Edmonds *et al.,* 2009). The high NUEs for SSA, according to the author, are due to the application of such little nitrogen fertilizer to an already reduced soil resource.

Because of the aforementioned issues, NUE has received increased attention from both agronomy and breeding research, as there is a greater sense of urgency for environmental care (Han *et al.,* 2015) and because fertilizers are expected to become more expensive in the future (Han *et al.,* 2015; Swain *et al.,* 2014). As a result of these environmental and economic considerations, cropping systems' NUE must be improved urgently. Agronomic approaches, such as mineral and organic nitrogen fertilization management, as well as the use of legumes in cropping systems and genetic advances in crop types, all influence nitrogen use efficiency positively.

In terms of water, only roughly 10%–30% of the available water (as rainfall, surface or groundwater) is used by plants for transpiration in both irrigated and rain-fed agriculture globally (Wallace, 2000). Rain-fed crops, on the other hand, are closer to 5% in dry and semi-arid areas, where water is scarce and population growth is significant. As a result, there is a lot of potential for improving water use efficiency (WUE) in agriculture, especially in locations where climate change has caused a shift in the start of the season and unreliable rainfall. This can be accomplished by raising the overall amount of water available for transpiration to plants and/or increasing the efficiency with which transpired water creates biomass.

Understanding the agronomic processes that influence N uptake, N use, and growth responses to N is critical for maximizing crop output while reducing environmental risks and improving WUE. Appropriate soil moisture management strategies, integrated soil fertility management, and logical crop rotation systems are examples of management practices that can improve NUE and WUE. Sha & Wu (2019) discovered various acceptable management approaches when examining soil and crop management strategies to promote improved crop productivity in sustainable environments. Nutrient management, site specific nutrient management (SSNM), integrated nutrient management (INM), integrated soil fertility management (ISFM), integrated soil-crop system management (ISSM), ridge-furrow mulching systems (RFMS), sustainable water management (SWM), conservation agriculture (CA), sustainable land management (SLM), vertical/sky farming, and integrated crop management are some examples of these practices. Incorporating legumes into a cereal cropping system provides a number of advantages in terms of increasing N supply through biological fixation. Depending on the species, such increases in N buildup also resulted in improved yields for later cereal crops given by legumes (Walley *et al.,* 2007; Zander *et al.,* 2016). For example, field pea and faba bean accumulate about 130 and 153 kg N ha^{-1}, respectively, in their above-ground biomass, while large amounts (30 - 60% of the total N accumulated) may also be stored in below-ground biomass (Peoples *et al.,* 2009). Organic fertilizers increase soil structure and release nutrients as they decompose, enhancing the soil's ability to hold water and nutrients (Rehim *et al.,* 2020), as well as aiding N fertilizer uptake efficiency (Eid *et al.,* 2018). As a result, the overall objective of this study was to assess the overall effects of cropping systems and soil fertility management on nitrogen use efficiency (NUE), water use efficiency (WUE), and wheat performance under various water harvesting methodologies (*T. aestivum* L).

1.2 Statement of the problem

Wheat production in Kenya's Njoro Sub-County, Nakuru, is being hampered by a number of issues, including poor soil moisture and nitrogen levels. Crop productivity is constrained more by water and nitrogen availability than by most other environmental conditions. Plant availability of macronutrients such as nitrate is mostly regulated by the amount of water available in the soil, and crops can become both water and nitrogen constrained during drought events. Due to low levels of soil N and moisture in Njoro Sub-County, low wheat yields have been observed, posing a threat to the population's food security and economic well-being. It is also predicted that the situation will deteriorate over time. Prolonged moisture stress is more likely to occur across both long and short seasons of the year in the years 2021-2065, according to projections, and the time of soil moisture stress will more than double in the first rainy season, from around 35 days to over 70 days on average. All of these projections served as the foundation for this study, which aimed to develop agricultural systems to minimize the long-term effects of low soil moisture and deteriorating soil fertility in Njoro Sub-County in order to ensure long-term wheat productivity.

1.3 Objectives of the study

1.3.1 Broad objective

The overall objective was to determine a sustainable agricultural system using appropriate water harvesting strategy, crop rotation and soil fertility management strategies for the enhancement of nitrogen and water use efficiency to contribute to increased wheat productivity in Njoro Sub-County.

1.3.2 Specific objectives

(i) To determine the effect of crop rotation on water and nitrogen use efficiency of wheat

(ii) To determine the effect of soil fertility management strategies on water and nitrogen use efficiency of wheat

(iii) To determine the effect of water harvesting strategies on water and nitrogen use efficiency of wheat grown under short term rotation systems.

(iv) To determine the effect of water harvesting, rotation and soil fertility management on wheat performance.

1.4 Hypotheses

(i) Crop rotation does not have a significant effect on water and nitrogen use efficiency of wheat.

(ii) Soil fertility management does not have a significant effect on water and nitrogen use efficiency of wheat.

(iii) Water harvesting does not have a significant effect on water and nitrogen use efficiency.

(iv) Water harvesting, crop rotation and soil fertility management do not have significant effects on wheat performance.

1.5 Justification of the study

Drought, heavy rains, and high temperatures brought on by climate change are already hurting agricultural production, earnings, and food security in Kenya, particularly in the Njoro

Sub-County. In the future, these variables are anticipated to offer even larger problems. Looking ahead to the years 2021-2065, extended moisture stress is expected to occur during both the short and long rainy seasons of the year, with moisture stress in consecutive days expected to more than double in the first wet season, from 35 to over 70 days on average (MoALF, 2016). All of these factors point to the need for robust soil-water-crop management methods that can endure future moisture and temperature stresses. To elucidate WH, CR, and SFM combinations that sustainably build soil capacities to provide N and water, increase N use efficiency, water use efficiency, and wheat productivity, this study evaluated water harvesting (WH) strategies, cropping sequences in the form of rotation (CR), and various soil fertility management (SFM) strategies.

1.6 The Scope and limitations of the study

The study evaluated selected crop and soil related management interventions mainly to enhance nutrient and water use efficiency of wheat in Njoro Sub - County. The field study was conducted for three years at the Kenya Agricultural and Livestock Research Organization (KALRO) Njoro Centre for three years. The study generated four outputs including appropriate packages on crop rotation regimes for enhancing NUE and WUE for wheat-potato cropping systems; ridges as soil moisture management tool for wheat (*T. aestivum*) based cropping systems; and quantified the contribution of legumes on soil fertility in cereal-potato cropping systems and ultimately a PhD thesis and at least two publications in refereed journals. During the implementation of the study, delayed funding by the sponsors and variability in weather conditions caused delay in the implementation of some planned activities.

CHAPTER TWO
LITERATURE REVIEW

2.1 General overview

Crop production supports human and animal populations with food, nutrition, fuel, and fiber, while plants convert atmospheric carbon to organic carbon. “Crop production techniques need a lot of water and fertilizers, particularly nitrogen (N)”. Currently, the global crop production systems consume around 70% of total fresh water extraction (2800 Km3) from many sources including surface rivers and groundwater, as well as more than 100 Kg N fertilizer (FAO, 2014; Fowler *et al.,* 2013). However, world agricultural output is severely limited by water and N availability, as well as poor environmental management (Mueller *et al.,* 2012; Rockstrom *et al.,* 2010). The gap between crop yields and the achievable yields (assuming enough water and nitrogen are available) is greater in greater in the developing nations as opposed to the developed ones. Due to improvements in water and soil N management, Mueller *et al.* (2012) predicted a 45 to 70% increase in global crop production for most crops (64% for maize, 71% for wheat, and 47% for rice). Because crop yields are generally restricted by both water and nitrogen, it is critical to enhance both water and nitrogen availability at the same time in order to benefit from their interaction effects. This is reinforced by the fact that “plant availability of macronutrients like nitrate is largely governed by the quantity of water available in the soil, and crops can become both water and nitrogen restricted during drought periods” (Plett *et al.,* 2020). To achieve such gains, a quantitative understanding of the water and nitrogen requirements of growing crops over time, as well as the water and nitrogen supplies provided by soil, atmosphere, fertilizers, animal manures, and crop residues over time, is required.

According to current trends, “global food production may need to quadruple by 2050 to feed the world's growing population (up to 9-10 billion people)”. The demand for grains (primarily wheat, maize, and rice), as well as fruits and vegetables, would rise (Alexandratos & Bruinsma, 2012; FAO, 2009; Ray *et al.,* 2013). Further, human diets are changing due to the effects of urbanization, globalization and the increases in prosperity of a part of the global population. According to observations by Bai *et al.* (2014), Foley *et al.* (2011) as well as Ma *et al.* (2013) more animal products (dairy, meat, and egg) as well as fruits and vegetables are being consumed worldwide. When compared to crop-derived food products, animal-derived food items generally require more water and N inputs. Thus, a unit of meat takes 3 to 10 times the amount of water and N as a unit of grain (Hoekstra & Mekonnen, 2012). Crop production methods worldwide have been driven mostly by changing preferences, but they also have important environmental consequences (Bai *et al.,* 2014; Ma *et al.,* 2013; Westhoek *et al.,* 2014).

Poor nutrition management results in inefficient nutrient utilization and, in many cases, significant nutrient losses. Due to significant "nutrient leaching losses on the one hand and poor nutrient release and utilization on the other, inadequate water management leads to low water use efficiency and possibly low nutrient use efficiency". According to Sutton *et al.* (2011) and Sutton *et al.* (2013), currently, "only about half of the applied fertilizer N is taken up by the crop, depending on crop type and management, leaving the un-utilized N to be accumulated in the soil temporarily and/or get lost through ammonia volatilization and denitrification, and/or is lost to groundwater and surface water bodies via leaching, overland flow and erosion". In China, for example, N recovery in the harvested crop is even lower than half, whereas N losses account for more than half of the applied fertilizer N (Ju *et al.,* 2009). Nitrogen losses to air and water bodies have had a variety of human health, environmental, and ecological consequences (Sutton *et al.,* 2011; Sutton *et al.,* 2013). Low water usage efficiency is frequently linked to squandering precious fresh water resources, resulting in depletion in many dryland locations throughout the world. As a result, future crop output is jeopardized (Foley *et al.,* 2011; Hoekstra & Wiedmann, 2014). Thus, efforts to improve water and nitrogen usage efficiency and reduce water and nitrogen losses are urgently needed.

2.1.1 Functions of Nitrogen

Being a key nutrient, N has specific relevance for the proper growth and development of plants. "Nitrogen (N) is main component of many organic substances (protein, nucleic acids, alkaloids etc), (protein, nucleic acids, alkaloids etc.)". It is a component of energy transfer molecules including adenosine diphosphate (ADP) and adenosine triphosphate (ATP), which play a vital role in energy consumption, transfer, and release in plant metabolism (Dunn & Grider, 2021). "Nitrogen is also found in nucleic acids (deoxyribonucleic acid and ribonucleic acid), which play an important role in plant genetic heredity".

2.1.2 Nitrogen losses through various processes

Denitrification, according to Bolan and Hedley (2003), is the microbial-mediated reduction of nitrogen in its nitrate form (NO3). It finally leads in the release of nitrogen gas (N_2) and nitrous oxide (N_2O) into the atmosphere, according to Fageria (2002). When there is a scarcity of oxygen, the population of microorganisms capable of converting nitrate to nitrogen through a process known as denitrification increases, resulting in nitrogen loss (Dobermann & Cassman, 2004). Aside from soil moisture content, NH4+-N and NO3 –N concentrations, as well as carbon content and temperature, can also affect the denitrification process within the soil-plague.

Depending on the type and management of N, it is also lost by leaching which is "the removal of nitrite or nitrate from the plant root zone by the flow of water through the soil is referred to as leaching". "Negatively charged nitrite (NO_2-) and nitrate (NO_3-) are observed to flow easily with water unless soils have a large anion exchange capacity". Thus every year, 55 Teragrams (Tg) of nitrate are expected to be leached from agricultural soils (Nieder & Benbi, 2008). When the soil is sandy in texture and contains enough water to cause nitrate migration across the soil profile, leaching losses of nitrogen occur. Because nitrate is a mobile type of nitrogen that is not firmly adsorbed on soil particles, it may readily be transported beyond the soil profile via a process known as leaching (Randall *et al.,* 2003). This method of N loss is especially important in places with heavy rainfall and light texture soils, where up to 50% of the N applied might be lost (Bolan & Hedley, 2003). The amount of applied nitrogen, the amount of water in the soil, and the permeability of the soil system are all key elements in determining how much nitrogen is leached from a crop production system (Davis *et al.,* 2003).

Ammonia volatilization is the process of converting NH4+-N into NH3 gas and releasing it into the atmosphere. This nitrogen loss process is proven to be more severe when organic manure and chemical nitrogenous fertilizers (NH4+ containing) are disseminated (Bolan & Hedley, 2003). Urea and urea-based fertilizers are more sensitive to volatilization losses when "sprayed to the surface and not immediately absorbed into the soil." Ammonia volatilization N loss is also more severe in alkaline soil and warm sunlight circumstances.

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2.2 Efficient nitrogen use

2.2.1 Nitrogen Use Efficiency (NUE)

The phrase "nitrogen usage efficiency" (NUE) is a broad concept that requires clarification. It is mostly an agricultural term having two distinct definitions that are used interchangeably when the term is used. The basic definition of nitrogen use efficiency is the efficiency with which plants eat and retain nitrogen in the soil. The rationale for this NUE definition stems from a plant's tendency to release nitrogen as nitrous oxide into the environment rather than retaining it in its body after absorption (Volpe *et al.,* 2016)

The three important components of nitrogen utilization efficiency (NUE) are nitrogen uptake efficiency (NU_pE), nitrogen uptake efficiency (NU_tE) in biomass generation, and nitrogen harvest index (NHI) (Ciampitti & Vyn, 2013; Masclaux-Daubresse *et al.,* 2010). In order to account for harvestable product use efficiency, NU_tE and NHI can be integrated into a single component. Breeders can improve the NUE of farming systems by developing cultivars with high agronomic nitrogen use efficiency (AgNUE). These cultivars may have a greater ability to produce a substantial amount of harvestable biomass per unit of nitrogen provided through fertilizers. In this case, each component of the multiple underlying physiological processes and (combinations of) features is important. "Root architecture, N absorption per unit of root length, leaf senescence and N remobilization in the plant, and NHI" are only a few of the many and varied traits (Barraclough *et al.,* 2010; Gewin, 2010; Malagoli *et al.,* 2005).

Various definitions provide some of the most essential agronomic and physiological terminology linked to the conceptual framework NUE. According to Dobermann (2007), NUE can be defined in a variety of ways in one of the numerous definitions. NUE, also known as partial factor productivity (PFP) (Cassman *et al.,* 1998), was defined as the ratio of yield to total N inputs in this study:

$$\text{Nitrogen use efficiency (NUE, kg kg}^{-1}\text{)} = G_y / N_{supply} \quad [1]$$

Where

G_y is grain yield in kg ha^{-1} and

N_{supply} is the sum total of soil N content at sowing, mineralized N and N-uptake in control (0 N applied) in kg ha^{-1}.

2.2.2 Nitrogen Utilization Efficiency (NU_tE)

Nitrogen use efficiency (NUE) is generally disaggregated into two parts as an integrative trait: uptake and utilization efficiency. The capacity to convert total plant nitrogen (TPN) during harvest to grain dry matter (GY / TPN) is measured by nitrogen utilisation efficiency (NU_tE). However, the focus of this section is on NU_tE, which the "crop's capacity to utilize applied N". Improved agricultural techniques, according to Hirel *et al.* (2007), can enhance NU_tE levels. A substantial and positive connection was found between grain yield and majority of the N use efficiency indicators of wheat, including NU_tE and NU_pE, in a research by Mansour *et al.* (2017).

2.2.3 Nitrogen Uptake Efficiency (NU_pE)

Nitrogen uptake efficiency (NUpE) is generally estimated as total plant nitrogen (TPN) at harvest divided by available N in the soil, or as the quantity of N taken up by the crop as a function of available N as determined by TPN/Ns, where Ns is the soil N available. The ability to absorb nitrogen (NUpE) is determined at a genetic level (Hirel *et al.,* 2007). Nitrogen uptake efficiency (NU_pE) fluctuates more than nitrogen utilization efficiency (NU_tE) under N limiting situations (Rumesh *et al.,* 2019). As a result, N uptake is primarily a root trait impacted by both root architecture and root function. One or more major gene families catalyze each of these forms' absorption and transport across cell membranes, and transport mechanisms are highly developed, with high substrate affinity and expression patterns that are frequently affected by dietary variables (Garnett *et al.,* 2013; Williams & Miller, 2001).

2.3 Consequences associated with low Nitrogen use efficiency (NUE)

Nitrogen cycling is a dynamic process that involves a variety of biochemical transformations within the soil-plant system, with some of these processes (ammonia volatilization, denitrification, leaching, and soil erosion etc) causing serious environmental contamination. The main environmental implications of decreased nitrogen usage efficiency of fertilizer N manifest themselves in a variety of ways. Groundwater contamination results from nitrogen that has been lost beyond the root zone of a plant system due to leaching. The amount of N lost by this process is determined by soil characteristics, soil and plant management techniques, agro-climatic conditions, as well as the manner and kind of N fertilizer applied

(Brady & Weil, 2002). Due to greater permeability to nitrate dissolved water, leaching is the most often documented route of N loss in light texture sandy soils (Baligar *et al.,* 2001). It has also been recorded in well-irrigated regions with a shallow water table and N fertilizer in the nitrate form. Due to the lower percolation of water beyond the root zone, paddy cultivation in lowland ecology with fine-textured soils (heavy soils) results in reduced N losses through leaching, whereas crops (e.g. Rice) grown in upland ecology with coarse texture soils (light soils) can result in significant leaching losses (Buresh *et al.,* 2004).

Eutrophication is another mechanism linked to a low NUE and it involves enriching water bodies with chemicals, particularly nitrogen (N) and phosphorus (P), which can promote excessive growth of aquatic algae populations is known as eutrophication". Eutrophication of water bodies is now a major problem across the world, since it may result in a lack of oxygen and the production of chemicals that are directly harmful to aquatic species as well as indirectly dangerous to animals and humans (Baligar *et al.,* 2001). "Eutrophication is caused by the loss of nitrogen (N) from fertilizer through runoff water from agricultural land".

The world's aquatic and forest ecosystems are particularly vulnerable to N deposition, and excessive N enrichment can impair ecosystem processes and services. Increased N deposition in ecosystems can result in global warming owing to increased emissions of N-based greenhouse gases, soil acidity due to excessive aluminum breakdown, and lower carbon stores in the soil (Burns, 2004). The greenhouse effect of N is a significant factor in climate change concerns. Denitrification produces nitrous oxide (N_2O), a significant N-based greenhouse gas that contributes to around 5% of total global climate change (Shoji *et al.,* 2001). Aside from that, excessive nitrous oxide emissions into the atmosphere might deplete the ozone layer. "One of the primary sources of N_2O is the loss of soil-applied N due to microbial degradation at increasing moisture levels". Around two-thirds of global nitrous oxide emissions come from agricultural soils (Mosier *et al.,* 2001).

2.4 Nitrogen use efficiency (NUE) and its importance in crop production

Agricultural intensification has resulted in soil and environmental deterioration in order to increase food production. "Crops use just a portion of the N fertilizer supplied, causing the rest to be leached or squandered, resulting in environmental damage. The cropping system in this example has a low NUE". Nitrogen use efficiency (NUE) varies per crop; for example, cereals are reported to have a NUE of 33% across the world (Rumesh *et al.,* 2019). According to Galloway *et al.* (2008) and Spiertz (2010), the threat of environmental deterioration will continue as long as the NUE dynamics are not sorted out, and the demand for more food to feed an ever-increasing human population. As a result, cropping systems must enhance their NUE that is usually influenced by a variety of agronomic methods, including mineral and organic N fertilizer management, soil moisture management, and the use of legumes in cropping systems, as well as improvements in the genetic characteristics of the crops in issue (Hirel *et al.,* 2011). Rainfall, which contributes directly to soil moisture, increases N mineralization, but excessive rainfall accelerates nitrate leaching, resulting in low NUE (Cabrera *et al.,* 2007; de Koeijer *et al.,* 2003; Sadras, 2002; Sadras & Roget, 2004).

2.5 NUE in Agronomy

A nutrient-efficient plant, according to Fageria *et al.* (2008), is one that generates a greater economic yield with a fixed amount of applied or absorbed fertilizer when compared to other or conventional plants under similar growth conditions. This definition emphasizes the plant's human usage, yield, and economic perspective, all of which are essential in the area of agronomy. One popular definition used in agronomy for calculating NUE is that of Moll *et al.* (1982), which refers to NUE as G_w/N_s, where G_w is grain weight and N_s is N supply. Nitrogen use efficiency (NUE) may be further split into at least two components, uptake efficiency (N_t/N_s) and utilization efficiency (G_w/N_t), assuming total N in the plant at maturity (N_t) is taken into account. The total NUE is determined by the product of these two components, which is G_w/N_s.

Nitrogen use efficiency (NUE) is generally broken down into two parts as an integrative trait: “NU_pE which is the capacity to collect N from the soil, and is generally calculated as total plant nitrogen (TPN) at harvest divided by available N in the soil”. “The capacity to convert TPN to grain dry matter (GY / TPN) is referred to as N utilization efficiency”. This would aid in reducing the massive N losses that have been observed as a result of declining NUE trends in agricultural systems across the world.

Nitrogen use efficiency (NUE) of agricultural systems has been declining across several continents over the last 50 years, owing to increased N inputs, inadequate N management, and the law of diminishing returns. The upshot of “declining NUE trends is that N losses have risen” (Ju *et al.,* 2009; Liu *et al.,* 2013). In the industrialized world, roughly half of the N fertilizer input is transformed into harvested goods, compared to 68% in the early 1960s, implying that about half of the N input is lost to the environment (Lassaletta *et al.,* 2014). In recent years, tight environmental restrictions and improved N management have resulted in a small improvement in NUE in Europe. "Differences in NUE levels have been observed between countries, which are due to differences in cropping systems, environmental conditions, and N management strategies".

Mansour *et al.* (2017) found significant differences in the two components of NUE, such as Nitrogen Uptake Efficiency (total NU_pE, which is a ratio of TPN/Ns, where TPN is total plant N at harvest and Ns is soil N available to the plant) and Nitrogen Utilization Efficiency (grain NU_tE), among different wheat genotypes at low and high levels of applied N. Nitrogen utilization efficiency (NU_tE) is derived using:

$$NU_tE\ (kg\ kg^{-1}) = \frac{[GY_f - GY_u]}{[N_f - N_u]}$$

Where GY_f is the grain yield of the fertilized plot (kg), GY_u is the grain yield of the unfertilized plot (kg) for each replicate, N_f is the N (grain plus straw) of the fertilized plot (kg), N_u is the N (grain plus straw) of the unfertilized plot (kg).

Low N levels (0 kg N ha^{-1}) resulted in greater NUE, total-NU_pE, and grain-NU_tE values than higher N levels (280 kg N ha^{-1}). In contrast to NU_pE, the data indicated a positive association between NUE and NUtE. The levels of NUE were shown to be consistently linked to grain-NU_tE and total NU_pE, and both parameters significantly rose when the amount of N fertilization dropped in all genotypes. In grain-NU_tE, the range of variance across genotypes was greater than in total-NU_pE.

Nitrogen use efficiency (NUE) genotypes can differ because to variations in N intake (Rodgers and Barneix, 1988) and N remobilization (Rodgers and Barneix, 1988; Van Sanford & MacKown, 1986). While Van Sanford and MacKown (1986) discovered that total-NU_pE accounted for roughly 54 percent (0.54) of the variance in NUE in 25 genotypes at a single rate of N (40 kg N ha^{-1}). Similarly, Le Gouis *et al.* (2000) found considerable genetic variability in total-NU_pE at both high (100 kg N ha^{-1}) and low (20 kg N ha^{-1}) N levels in a study of 20 wheat genotypes, accounting for roughly 64% (0.64) and 30% (0.30) of the variance in NUE at high and low N levels, respectively. This might explain why contemporary wheat cultivars have lower

NU_tE and, as a result, lower NUE, whereas high biomass genotypes have greater total-NU_pE (Feil, 1992). Barraclough *et al.* (2010), on the other hand, found that genetic variation in NUE was linked to variations in grain-NU_tE rather than overall NU_pE at various N rates. Asplund *et al.* (2014) found that total-NU_pE was greater in the field and grain-NU_tE was higher in the greenhouse, with similar overall NUE in both settings. "In all field and greenhouse experiments, genotypic rankings for NUE and total-NU_pE were comparable, while grain-NU_tE was different".

When it comes to wheat, the NUE is less than 60%. (Duan *et al.,* 2014; Haile *et al.,* 2012; Hawkesford, 2012). However, Rahman *et al.* (2011) reported NUE values ranging from 28.8 to 40.0 kg grains per kilogram N applied, with N rates ranging from 80 to 120 kg N ha^{-1}, depending on genotype and N levels impact. Nitrogen uptake efficiency (NU_pE) (Sadras & Lemaire, 2014), NU_tE (Barraclough *et al.,* 2010), and N recovery efficiency (NRE) have all been blamed for the heterogeneity of contemporary cultivars' responses to NUE (Guo *et al.,* 2014; Kichey *et al.,* 2007; Pask *et al.,* 2012).

Other traits linked to NUE, such as phytomass accumulation (Giambalvo *et al.,* 2010) and leaf chlorophyll content (Silva *et al.,* 2014; Wani *et al.,* 2011), can be used for indirect cultivar selection because they use N more efficiently. Cropping system methods can also be used to improve NUE. Cereals, for example, which are the biggest consumers of N fertilizers among field-grown crops, have a greater NUE when grown after a legume crop than when produced after a fallow or non-legume crop (Uttah *et al.,* 2019). Plant biomass and long-term soil organic carbon (C) rise when N fertilizer is administered at higher rates than required for maximum production (Raun *et al.,* 1998), but NUE declines.

2.6 Factors influencing Nitrogen losses

Different forms of losses linked with the soil plant system impact nitrogen use efficiency (NUE). The main causes of decreased NUE in production systems are gaseous nitrogen loss to the atmosphere and N leaching beyond the root zone of crops (Mosier *et al.,* 2001). "Optimal circumstances for plant growth and development can enhance plant N demand, but this need may not be satisfied due to large N losses, resulting in low applied N recovery".

2.6.1 Management strategies to optimize nitrogen use efficiency (NUE)

Nitrogen use efficiency (NUE) and crop development may be improved using various management techniques that include both the amount of N fertilizer used and when it is applied. Both components are dependent on the availability of soil water, which is a direct result of weather. However, in the face of climate change, when weather prediction is restricted, adopting a scheduled N fertilizer application approach (time of N application) has become increasingly challenging (Stuart *et al.,* 2014). As a result of climate unpredictability, farmers are losing control over N mineralization, crop growth, and NUE. As a result, farmers are sometimes obliged to raise N application rates during periods of excessive rainfall, which might result in excess N leaching and hence poor NUE. However, using low N fertilizer rates to prevent storing surplus N in soils and therefore increasing NUE raises the risk of transitory crop N shortage since the N given by the soil would not fulfill plant needs. Thus, minimizing N leaching via careful nutrient management and boosting crop yields by the inclusion of legumes in the cropping system that improves the advantages from N fixation are two approaches to increase NUE. This improves N mineralization (release) from legume crop residues over time, resulting in higher soil organic matter (SOM) levels when organic fertilizer is added. It's a crucial step since SOM functions as a reservoir and controller of soil water, mostly independent of rainfall. Other novel techniques, such as breeding procedures, are needed to increase crop NUE in either over-fertilized and under-fertilized environments, as well as systems with nitrogen shortages or other pedo-climatic limitations. According to (Cassman *et al.* (2002), to maximize crop production with little N input and decrease environmental risks associated with excess N in the soil, it is critical to understand the mechanisms and plant characteristics that regulate N absorption, distribution, and growth responses to N.

Kenya's agriculture has traditionally been reliant on rainfall, however increasing industrialization has had a significant negative influence on the environment during the previous two decades (Lusweti, 2012). Precision agriculture is thus required to coordinate crop nutrient demand and soil moisture levels in order to avoid wasteful input usage and environmental hazards. "Precision agriculture (PA) would play a significant role in increasing agriculture production sustainability in this situation". Precision farming is a farm input management method based on information and technology, with the goal of identifying, analyzing, and managing spatial and temporal variability in all elements of agricultural productivity in fields

(Lusweti, 2012). Measurement of N variability in soils, followed by application of the right amount of N at the right time using a variable rate applicator, remote sensing, geographic information systems (GIS), and global positioning systems (GPS) technology, could all help farmers improve NUE under specific field conditions. In advanced management techniques, remote or local N sensors can be utilized to determine crop demands for supplementary N. (Schmidt *et al.,* 2002). These techniques include applying N fertilizer at the right time and in the right place to satisfy the demands of plants in different parts of the landscape. Precision farming improves maximum profitability, sustainability, crop performance, land resource protection, and environmental quality maintenance or improvement (McBratney *et al.,* 2003).

Site Specific Nitrogen Management (SSNM) is a concept that entails field-specific N management techniques that incorporate quantitative information of field-specific variations in crop N demand and projected soil N providing capacity (Dobermann *et al.,* 2004). The basic premise of this idea is to achieve the best possible synchronization between N supply and demand for plant development (Giller *et al.,* 2004). Site Specific Nitrogen Management (SSNM) is divided into two types based on when and what sort of choices are made: prescriptive SSNM and corrective SNNM (Dobermann *et al.,* 2004). "The amount of N and when it should be applied should be determined prior to sowing based on the soil's ability to provide N, the estimated crop N demand for the desired yield, and the expected N efficiency of the fertilizer products to be employed". Corrective N management, on the other hand, entails the use of diagnostic instruments to assess the N condition of a standing crop. The analysis of these collected data is used to make judgments about when and how much N should be applied (Schroeder *et al.,* 2000). For corrective N management in cereals, chlorophyll meters (SPAD), nutrient experts, and leaf color charts (LCC) have all shown promise in recent years (Olesen *et al.,* 2004; Singh *et al.,* 2012).

By applying the **R**ight fertilizer, at the **R**ight quantity, at the **R**ight time (synchronization), and at the **R**ight place (synlocalization), the NUE of fertilizer N applications may be enhanced (IPNI, 2012). Nutrient expert is a developing management diagnostic tool in this respect, in which input variables such as fertilizers are administered in the appropriate amount, at the right place, and at the right time (variable rate application) based on crop-plant demand (Pampolino *et al.,* 2012). It aids in increasing input efficiency, reducing fertilizer costs, and ensuring the long-term use of natural resources. As an advanced technique, combining the application of water and nitrogen by precision drip irrigation (Fertigation) can assist to enhance both WUE and NUE. However, because of the high investment and maintenance costs, fertigation is mostly employed in high-value crops rather than grain crops. The optimization of water and N applications, however, remains difficult due to variable rainfall and frequently uncertain N supply from soil (Phogat *et al.,* 2013).

In intensive maize and wheat-based systems, proper nutrient management should seek to provide enough fertilizers depending on the need of the component crops and apply them in methods that reduce loss and increase usage efficiency (Basso *et al.,* 2011). Ensure an optimal density of crops, evaluate ongoing nitrogen management practices, establish a meaningful yield goal, determine the quantum of indigenous soil N, the required N fertilizer rates for above selected yield goal, translate fertilizer N rates into fertilizer sources, and develop an efficient ap using nutrient expert are all steps involved in smart N management using nutrient expert (Majumdar *et al.,* 2013). In order to enhance N recovery, Integrated Nutrient Management (INM) entails making the best use of indigenous N components such as crop wastes, organic manure, biological fixation, and chemical fertilizer, as well as their complementing interactions (Olesen *et al.,* 2004). The benefits of combining organic and inorganic N are attributable to either a better physico-chemical soil environment or improved root development and increased availability of secondaryN and micronutrients (Singh *et al.,* 2012). Understanding and using these beneficial interactions among plant nutrients is critical for boosting returns to farmers in terms of improved yields, soil quality, and NUE of applied N (Aulakh & Malhi, 2004). The combination of N with secondary nutrients and a variety of micronutrients might result in significant increases in yield and NUE. As a result of the complementary effects, using N from all available sources in a balanced and prudent manner would improve the soil physico-chemical environment and increase land productivity.

Several high-impact studies on the influence of INM techniques on agricultural productivity have been done. “Integrated Nutrient Management (INM) gives crops a well-balanced diet and reduces the negative impacts of hidden deficiencies and nutrient imbalance”. The best yields were obtained with vermi-compost treatments of 15 tonnes ha^{-1} and the prescribed NPK dosage (Nehra & Hooda, 2002). The use of organic manure and crop residue has a substantial impact on the physical characteristics of a soil in rice-wheat system (Singh *et al.,* 2007). In order to achieve optimum production and preserve soil fertility, INM entails the sensible and effective use of multiple types of nutrients, such as mineral fertilizers, organic manures, and bio-fertilizers, in an integrated way.

Increased nutrient availability and N use efficiency were achieved by combining organic manures with chemical fertilizers, resulting in a sustained output. In INM, the use of organic manures aids in the prevention of various nutritional shortages (Satyanayarana *et al.,* 2002). For example, using organic manures such FYM at 10 tonnes ha^{-1} and vermi-compost at 5 tonnes ha^{-1} combined with 60 kg P_2O_5 ha^{-1} or 40 kg P_2O_5 ha^{-1} + PSB and 40 kg S ha^{-1} resulted in the highest wheat grain and straw yields (Patel *et al.,* 2014). As part of the INM approach, a combination of environmentally friendly and low-cost bio-fertilizers, as well as organic and inorganic fertilizers, play a key role in plant nutrition (Patel *et al.,* 2011). Apart from biological N fixation (BNF), bio-fertilizers are thought to act as growth regulators, resulting in a significantly greater response on many growth and yield characteristics (Saiyad, 2014). As a result, judicious application of organic manure, bio-fertilizer, and organic fertilizer aids in wheat production sustainability.

There are fertilizer formulations that can increase fertilizer use efficiency (FUE) of applied nutrients by minimizing nutrient losses in the production system and increasing their beneficial usage in plants (Umesha *et al.,* 2017). These fertilizers are based on one of two philosophies: "slowing the rate of nutrient release or interfering with nutrient transformation pathways to decrease losses". Slow or controlled release fertilizers (CRF), N inhibitors, and N nitrification inhibitors are some of the fertilizers that help to improve (FUE).

Fertilizers with a slow or controlled release and N inhibitors are two significant types of fertilizers. The kind of nitrogenous fertilizer used has an important impact in regulating different N losses and therefore altering nitrogen availability and recovery. When compared to amide and ammonium-containing N fertilizers, nitrate-containing fertilizers are more vulnerable to leaching. Ammonium and amide-containing fertilizers, on the other hand, are more susceptible to volatilization than nitrate-containing nitrogen fertilizers. A variety of slow release fertilizers that have the ability to decrease different N losses and enhance NUE are currently being offered in order to regulate the undesired loss of applied nitrogen (Giller *et al.,* 2004). These fertilizers contain chemicals that have the ability to reduce nitrogen losses by delaying the release of nitrogen, thereby increasing the synchronization of crop demand and soil N supply. In India, neem-coated urea is a popular and effective slow-release nitrogen fertilizer. Controlled release fertilizers, on the other hand, account for only 0.15% of overall nitrogen fertilizer usage.

While N nitrification inhibitors promote the delayed release of nitrogen from applied fertilizers in order to prevent leaching losses. Ammonium ions (NH_4^+) can, for example, be absorbed on soil colloids and held for extended periods, providing continuous nourishment to plants while reducing leaching and de-nitrification losses and so increasing nitrogen usage efficiency. It has been reported that nitrification inhibitors are used to prevent the conversion of ammonium-N to nitrate-N and to provide a greater concentration of ammoniacal nitrogen in the soil medium, therefore increasing NUE and crop production (Shivay *et al.,* 2001). Dicyandiamide (DCD) is a commercially available nitrification inhibitor that has been widely utilized in rice production (Bharti *et al.,* 2000). Farmers in Kenya, for example, seldom utilize these fertilizers because to their high cost and scarcity.

2.7 Green manure to enhance N availability

Green manuring is possible with a broad variety of bean species. In comparison to non-leguminous crops, "legumes are superior green manure crops because they have the ability to fix atmospheric nitrogen into the soil" (Meena *et al.,* 2018). In most grain legumes, annual N accumulation ranges from 20 to 300 kg ha^{-1} in fodder and perennial legumes (Singh *et al.,* 2012). Plants for smart green manure crops should have a few key characteristics, including the ability to produce large amounts of dry matter, the ability to fix atmospheric free nitrogen, and the ability to be cultivated with minimal cultural practices, fast growing, and short duration in order to fit easily into intensive cropping systems such as annual crop rotation (Sharma *et al.,* 2011). The amount and quality of residue available, soil type and fertility status, soil acidity, microbiological diversity, soil moisture status, and temperature regime all have a role in the beneficial benefits of these green manure crops (Mary & Recous, 1994). Green manure decomposes in the soil, releasing the stored N for use by the subsequent crops.

Between 4 and 30% of the total N absorbed by a subsequent cash crop might originate from the mineralization of green manure crop waste, depending on the kind of green manure soil and management (Fageria, 2007). As a result, "green manure has the ability to provide part of the N requirements of cereal crops like wheat in low-input situations when the expense of appropriate inorganic fertilizer usage is out of reach for the resource-poor farmers". Green manure residues substantially enhanced wheat yield characteristics, as well as grain and straw yields (Hoque *et al.,* 2016). Green manures also had a substantial impact on wheat grain, straw, and total N absorption.

2.8 Crop rotations to enhance nitrogen use efficiency (NUE)

Crop rotation is defined as an appropriate sequence of crops farmed in a recurrent succession on the same piece of land (Gan *et al.,* 2003). To maintain the long-term stability of the production system, optimal crop sequences ensure effective use of precise agricultural resources, particularly mineral nutrient and soil moisture by crops (Singh *et al.,* 2012). Enhancing N recovery in crops requires the use of appropriate crop sequences. Legume-cereal rotation is an age-old technique that has been advocated as a good crop management strategy for enhancing soil health and crop system production (Yang *et al.,* 2020). Legume crops have the ability to fix free atmospheric nitrogen, reducing the amount of nitrogen required by subsequent crops in the sequence. The narrow C: N ratios of legume residues, according to Gan *et al.* (2003), can enhance the physical, chemical, and biological environment of soil by increasing total carbon stock and improving N availability to crops.

Crop rotation aids not only in the control of diseases, pests, and weeds, but also in the supply of nitrogen through nitrogen fixation and the notion of catch crops (Askegaard *et al.,* 2006). Crop rotation also aids in the growth of soil organic matter (SOM), particularly when wastes are absorbed into the soil, as well as the long-term improvement of soil structure. Increases in residual N in the optimal cropping system are another advantage of legumes in a crop cycle (Kopke, 2004). Because various legume species have varying nitrogen-fixing capacities, the total value of legumes varies. If just seeds are collected, net soil N accrual from grain legume residue assimilation can be as high as 140 kg N ha^{-1}, depending on the legume species (Giller, 2001). For example, Dolichos lablab (*L. purpurea*) can produce up to 0.5 tonnes ha^{-1}onnes of nitrogen (500 kg of dry matter biomass over 4 months) through symbiotic fixation and leafy decay (FAO, 2012; Valenzuela & Smith, 2002), whereas green pea can only fix between 12.4 and 21.8% of this amount (Mercinkeviciene, 2008).

Crop rotation with legumes also enhances soil physical, chemical, and biological conditions, increasing soil nutrient availability (Bagayoko *et al.,* 2000; Giller, 2001; Loewy, 1987; Yusuf *et al.,* 2009a). Crop rotation affects NUE and causes variations in diverse N sources, influencing plant availability (López-Bellido & López-Bellido, 2001). Some studies that looked at certain N efficiency indicators came to the conclusion that rotation is more efficient than monoculture (Badaruddin & Meyer, 1994; Soon *et al.,* 2001; Yamoah *et al.,* 1998). Dawson *et al.* (2008) validated this viewpoint in their study of over 100 literatures on the issue. This might be due to the fact that in rotation, crop N extraction and the N dynamic are more synchronized than in monoculture (Pierce & Rice, 1988).

Integration of legumes into cropping systems in Nigeria's northern Guinea savanna (NGSN) has been utilized as a resource management method to reduce energy use, cost, and pollution potential of inorganic fertilizer usage, as one example (Yusuf *et al.,* 2009b). Crop rotation using legumes, on the other hand, cannot meet all of the non-legume component of the maize-based cropping system's nitrogen requirements. This is because the existing practice of harvesting all above-ground biomass contributes significantly to a negative soil nitrogen balance (Sanginga *et al.,* 2002). To get a larger yield, more N fertilizer would be required. However, N fertilizer management may change depending on the cropping scheme. Changing the time of N fertilizer application to cereal in monoculture and rotation has been shown to enhance production, N usage efficiency, and N uptake efficiency (López-Bellido *et al.,* 1996). In the Njoro Sub-County, no studies have been done to evaluate the N usage efficiency of cropping systems, and no information on the effectiveness of the current technique of fertilizer application to wheat in various cropping systems is available. Regardless of the preceding culture in the rotation, an application of roughly 26 kg ha^{-1} is suggested. Under extremely dry or damp conditions, wheat may not respond to fertilizer N.

2.9 Water harvesting

In situ water harvesting using simple technologies allows for more water penetration, temporarily impounds water on the soil surface to enhance infiltration opportunity time, extends the availability of moisture to the crop, and allows the crop to thrive in unpredictable rainfall circumstances (Srinivasrao & Gopinath, 2016). Soil porosity, infiltration, and soil hydraulic conductivity are all improved by good in situ soil and water conservation measures, which increases soil water storage and promotes crop development (Srinivasrao *et al.,* 2016). The amount and distribution of rainfall, slope and soil type, depth and texture, especially clay content and clay type, which greatly influence water holding capacity and hydraulic conductivity impacting runoff and soil erosion, all influence the selection of appropriate soil and water conservation for a location (Pathak *et al.,* 2005).

In vertisols in Madhya Pradesh receiving less than 750 mm rainfall, the ridge and furrow method of sowing has been shown as an in situ moisture conservation and planting strategy in diverse crops such as pigeon pea, black gram, green gram, and soybean. When compared to farmers' practice of flatbed planting at many places, crops fared better under the ridge and furrow technique of sowing, with seed yields increasing by 22% in pigeon pea, 28% in black gram, 39% in green gram, and 27% in soybean.

Furthermore, despite prolonged dry spells during the crop season in 2014, in situ water harvesting through planting of black gram, green gram, and soybean in ridges and furrows resulted in yields of 0.5, 0.6, and 1.3 tonnes ha^{-1}, respectively, in Alfisols of peninsular India with rainfall less than 750 mm (Ren *et al.,* 2017). In the Datia district of Madhya Pradesh, ridge and furrow soybean planting yielded 1.1 tonnes ha^{-1} compared to 0.8 tonnes ha^{-1} in traditional planting. When compared to without leveling and banding, other water harvesting strategies such as land leveling and compartmental banding resulted in a 15–20% higher yield of finger millet. Trench cum banding was applied in various areas and was proven to increase crop yields by 12–30% compared to no banding. During heavy rainstorms, the majority of the top soil from the farmed fields was retained in the trenches, preserving fertile top soil and providing for the safe disposal of surplus precipitation. In Kenya, in situ moisture conservation methods such as slope plowing and contour banding have been shown to enhance crop yields when compared to no banding (Karuku, 2018). As a result, adopting in-situ rainwater collection techniques for improved soil and water management is a viable option.

2.9.1 On-Farm water harvesting technique

The tie ridge system, which connects ridges with cross-ties over the intervening furrows, is a step forward from the classic ridge-furrow method. The technique creates a series of rectangular depressions that collect rainwater. Except for a strip up to one-third of the row width, the soil is kept undisturbed from harvest to planting in the tie ridging method (Serme, 2014). To create a succession of basins for holding water, ridges (30 cm high) and ties (cross ridges, 20 cm high) are built. To avoid runoff water, the ridges should be spaced 90 cm apart and cross ridges formed at 2.5 m intervals manually (Miriti *et al.,* 2007). During the crop's growth season, the ridges are reshaped. Tie ridging decreases surface bulk density, increases soil water retention and available water holding capacity, and preserves soil fertility by minimizing losses of soil nutrients in surface runoff (Hulugalle, 1990; Mwende, 2019).

In Kenya, tie water harvesting has primarily been employed in semi-arid and desert areas. According to studies done in Kenya, tie ridging combined with integrated fertilizer management had the potential to increase crop productivity in Kenya's semi-arid zone (Miriti *et al.,* 2007). Chepkemoi (2014) found that sorghum intercropping and crop rotation under tie ridges with Minjingu Rock Phosphate (MRP) and Farm Yard Manure (FYM) treatment is a feasible method for increasing soil moisture, nutrients, and crop production. In Nigeria, Chiroma *et al.* (2008) found that the grain production of pearl millet was higher than 35% when compared to flat planting. Belay *et al.* (1998) found that combining tie ridge with crop residue and mineral fertilizer boosted maize grain production by 20% in Ethiopia. According to Yoseph & Gebre (2015), maize grain production gained from tie ridge (3625 kg ha^{-1}) was 55.72% greater than farmers' practice (1605 kg ha^{-1}). In a research done in Mali, tie ridge enhanced grain yields of sorghum in rotation with legumes by 10% compared to simple ridging in the Sahelian zone under low average rainfall (Kouyaté *et al.,* 2012). According to a survey of the literature, no research on tie ridge to assess NUE of wheat has been conducted in Kenya.

2.10 Effect of water harvesting on nitrogen use efficiency (NUE)

Rainwater harvesting (RWH) has been used in all of history's great civilizations for nearly 4000 years (Worm & Hattum, 2006). In the Middle East, North Africa, and East Asia, these procedures are extensively documented; however, nothing is known about them in Sub-Saharan Africa. Traditional knowledge has been acknowledged for its value in small-scale rainwater harvesting (RWH) systems and other soil and water conservation measures.

Although traditional RWH techniques do not have a well-documented history in Sub-Saharan Africa, they do exist and are often neglected despite their significant contributions. Some RWH techniques, such as earth bunds, have traditionally been an essential strategy for some agro pastoral tribes in the Horn of Africa, much like stone bunds and 'Zai Pits' have been in Western Africa (Critchley, 1991b). Traditional RWH methods have been particularly essential in dryland settings, where rainwater conservation is critical for livelihood and food survival. In Kenya, however, RWH techniques such as run-off harvesting may be described as the collection of run-off for productive use. (Anonymous, 1997; Pacey & Cullins, 1999) Others describe RWH as the collecting and concentration of runoff for productive uses in arid and semi-arid environments, such as crop, fodder, pasture, or tree cultivation, livestock, and household water supply (Fentaw *et al.,* 2002; Gould, 1999; Mutunga, 2001). The endeavor to gather water was prompted by the fact that during the major seasonal rainfall period, a large amount of water is generally lost due to a variety of factors such as run-off and evaporation. Harvesting rain water as either diversion or in-situ conservation has been a popular technique to profit from run-offs and other sources of water losses. By 2050, worldwide grain yields would have to quadruple due to rising global population and shifting consumer preferences toward meat-based diets (Tilman *et al.,* 2011).

Under marginal soil moisture conditions, wheat production sustainability is dependent on improved soil water storage and effective utilization during fallow (Khan *et al.,* 2020). As a result, it's critical to look for management techniques that can improve water and nitrogen usage efficiency (Fu *et al.,* 2014; Zhang *et al.,* 2009). Enhancing N usage efficiency as a means of sustaining smallholder crop production in Sub-Saharan Africa under changing climatic circumstances necessitates soil and water management adaptation methods (Lebel *et al.,* 2015). Rainwater harvesting (RWH) has been found to have a significant benefit in grain production in Africa, among the ways to integrate soil and water management. Rainwater harvesting (RWH) has the potential to bridge up to 40% of the yield gaps caused by water shortages under current conditions, while projections put it at 31% in the 2050s under climatic conditions, thus providing an alternative to irrigation from scarce or inaccessible groundwater resources during the main growing season for maize (Lebel *et al.,* 2015).

Wheat is generally planted on seedbeds that are prepared in various ways depending on the soil type and weather circumstances. Seed bed preparation is primarily used to suppress weeds and retain moisture for future crops in all conditions. Rainwater harvesting (RWH) has been used to achieve these goals using a variety of methods, including ridge and furrowing, among others. The RFRH method has been hailed as a potential water-saving planting strategy for dryland farming, however the effects of various fertilizer rates (N: P) on plant nutrient absorption and NUE are yet unknown (Lian *et al.,* 2017).

2.11 Water use efficiency (WUE)

Different authors define water usage efficiency (WUE) in different ways. Water use efficiency (WUE) is the total quantity of water required to grow the crop over the season, according to Hunt & Kirkegaard (2012), and comprises transpiration (water used by the plant to grow), evaporation (water lost from the soil surface), run-off, and deep drainage. When analyzing agricultural production systems from the standpoint of water usage, the word water use efficiency refers to production per unit of water consumed, although WUE is generally defined as a ratio of output-to-input (Sadras *et al.,* 2014), WUE is commonly defined as crop yield over evapo-transpiration (ET) (Bouman, 2007):

$$WUE = Y / ET \quad [2]$$

WUE is commonly represented in kilograms per meter squared, with Y equaling harvested crop yield (kg ha^{-1}) and ET equaling evapo-transpiration (m3 ha-1). The total of soil evaporation (E) and crop transpiration (T) is evapo-transpiration (ET) (Kang *et al.,* 2002; Siahpoosh & Dehghanian, 2012; Zhang *et al.,* 2006). Only T is a direct result of crop production, whereas E is a result of 'unproductive' water loss. Soil evaporation (E) can be significant, particularly in dry and semi-arid locations where rainfall is unpredictable. As a result, the key challenge in rainfed agriculture is 'how to convert unproductive water loss (E) into productive water usage (T)'.

Unfortunately, due to the difficulty and expensive expense of differentiating E and T, the partitioning between E and T is frequently unclear. As a result, rather than reporting E and T individually, crop water usage is typically reported as evapo-transpiration (ET) (Kang *et al.,* 2009; Zhang *et al.,* 2010). Due to a lack of quantitative knowledge on E and T partitioning, determining how much of the evaporative water loss may be utilised to increase yields through suitable interventions is challenging. Fertilization can boost root growth and early crop development, resulting in a bigger, earlier plant canopy and lower E level. Planting density can be increased to improve plant canopy and decrease E. However, there may be trade-offs; for example, eating too much water early on may lead to water stress later on. Minimizing unfavorable trade-offs necessitates a mathematical knowledge of the crop growing seasons' water balance.

2.11.1 Importance of Water- Use Efficiency (WUE)

High yields and WUE may be accomplished by implementing management methods such as water harvesting, crop rotation, and suitable soil fertility management practices that maximize rainfall collection and storage, as well as subsequent extraction of accessible soil water (Kirkegaard & Hunt, 2013). This aids in increasing the efficiency with which available moisture is utilized, as well as reducing the severity of water deficiencies during critical crop growth periods. There may also be interactions between other management methods, like as variety selection and sowing timing, which might restrict yields and WUE if not well matched (Sadras & McDonald, 2012).

2.11.2 Effect of Crop management on water use and water use efficiency

Crop water use (WUE) and yield are influenced by both the amount and distribution of rainfall. Farmers have no control on rainfall, but they may impact how much and how effectively rainwater is used by crops by changing crop and soil management methods. Because yield (or biomass) per millimeter of crop water consumption is defined as water use efficiency, management methods that create high yields have the potential to enhance water use efficiency. Regardless of management technique, crops in arid areas tend to utilize the majority of the available water. While debates on WUE frequently center on grain production, it's crucial to remember that crop management's primary goal is to maximize profit, not WUE or yield.

High yields and WUE can be accomplished by using management methods such as water harvesting schemes and legumes that can maximize rainfall collection and storage, as well as subsequent extraction of accessible soil water (Kirkegaard & Hunt, 2013). This aids in increasing the efficiency with which available moisture is utilized, as well as reducing the severity of water deficiencies during critical crop growth periods. There may also be interactions between other management methods, like as variety selection and sowing timing, which might restrict yields and WUE if not well matched (Sadras & McDonald, 2012). Profit-generating management methods will boost the economic efficiency of water use (Kenya shillings mm^{-1} of crop water use). On-farm WUE is varied, according to several studies, and while part of this is due to environmental variables including soil type, vapor pressure deficit (VPD), and rainfall event timing, much of the variation is attributable to crop management (Sadras & McDonald, 2012). Regional variances in sowing rates, fertilizer management, row spacing, and sowing timing indicate management methods that are often tailored to meet local patterns of rainfall and water availability.

2.11.3 Effect of crop rotation on water use efficiency (WUE)

The most frequent consideration for WUE is for individual crops; however, management in previous years or seasons has an impact on WUE of the present crop because it impacts the quantity of accessible soil moisture and soil nutrients, among other things (Hatfield & Dold, 2019). Legumes in the crop rotation are an efficient strategy to increase WUE by increasing available nitrogen, accumulating crop residues, and reducing disease incidence (Ullah *et al.,* 2019).

When wheat is planted after a legume, measurements of WUE in crop rotation systems indicate consistent gains in water use efficiency. Growing wheat after lupins increased total water usage by 11% (186 mm vs. 168 mm) and WUE by 26% (7.9 kg ha^{-1} mm^{-1} vs. 10.0 kg ha^{-1} mm^{-1}) in Western Australia, compared to continuous wheat. In another Queensland research, planting wheat after chickpeas boosted WUE by 27% compared to continuous wheat sowing (11.7 kg $ha^{-1}mm^{-1}$ compared to 9.2kg $ha^{-1}mm^{-1}$). Because the "mobility of plentiful free NO_3^- ions in soil is dependent on the water status or soil moisture content, such increases in WUE were proportionate to the quantity of Nitrate-N present in the soil" (Plett *et al.,* 2020).

Given the ever-increasing demand for restricted freshwater and soil resources, it is becoming increasingly obvious that feeding tomorrow's population will entail a major part of enhancing water productivity within current land usage, as additional arable land is scarce (Karrar *et al.,* 2012).

2.11.4 Effect of nitrogen availability on water use efficiency

Water use efficiency (WUE) and photosynthesis are inversely correlated with nitrogen shortage, resulting in a decrease in above-ground dry matter per unit transpiration (Savin *et al.,* 2015). When nitrogen-deficient crops were compared to well-fertilized controls, consistent decreases in above-ground dry matter per unit transpiration of up to 50% were found. This might be due to the low biomass/transpiration ratio (Brueck, 2008) and high evaporation/transpiration ratio associated with narrow canopies in nitrogen-deficient crops (Savin *et al.,* 2015). Because of the decreased root system and canopy caused by nitrogen shortage, the crop's capacity to collect soil water and nutrients was diminished. As a result of the reduced canopy providing less shade to cover the soil surface, soil evaporation increased. This was accomplished via a 28mm increase in water usage and a 41mm reduction in unproductive soil evaporation. With a high rate of N, dry matter per unit of water usage increased from 17 to 28 kg ha^{-1} mm^{-1}, and grain yield per unit water use increased from 5.3 to 8.4 kg ha^{-1} mm^{-1}. This increase in WUE can be explained by the fact that it came at the cost of a lower yield per unit of nitrogen fertilizer. Wheat, rice, maize, canola, and forage grasses, among other crops, have all been shown to have a nitrogen-driven trade-off between water and nitrogen usage efficiency (Sadras & McDonald, 2012). This trade-off has the crucial effect that achieving high water usage efficiency may need nitrogen rates that are sometimes too expensive, too hazardous, or environmentally unsound.

2.12 Summary and knowledge gaps

This literature review aimed to demonstrate how smallholder farmers in Kenya may benefit from sustainable agricultural intensification in order to strengthen their agricultural systems' resilience. Agriculture is a socio-ecological system that is typically managed to produce, distribute, process, and consume food, fuel, and fiber for the benefit of humans. As a result, agricultural resilience should be constructed to expand beyond the farm in light of changing climates and the often encountered weather unpredictability in terms of the on-set of seasonal rainfall. The goal of this chapter was to demonstrate how the wise use of inorganic and organic N sources in appropriate cropping systems combined with sustainable soil water management may serve as the foundation for resilience through the adoption of land use strategies that support this attribute. The following knowledge gaps were discovered in the literature review and addressed in this study. This includes an acknowledgement that the feasibility of integrated soil fertility management and water harvesting in a sustainable water harvesting practices in terms of sustainable wheat productivity, soil nitrogen, and water use efficiency had not been adequately investigated in the context of smallholder wheat farming systems in Kenya's Njoro Sub-County. The incorporation of legumes in the crop rotation cycle was also investigated as part of the INM system in this study. Further study was required to increase the flexibility of the wheat growing method in this Rift Valley region.

CHAPTER THREE

MATERIAL AND METHODS

3.1 Description of the study site

The study took place at the Kenya Agricultural and Livestock Research Organization (KALRO), Njoro Centre (GPS Coordinates: Latitude -0.342644; Longitude 35.946747; Elevation of 2172 m above sea level) in Njoro Sub-County, Kenya, for three seasons between 2014 and 2016 (Figure 3.1). The location is located in the Agro-ecological zone LH3 (AEZ LH3), which has a bi-modal rainfall pattern (Jaetzold & Schmidt, 2011). The area receives around 960 mm of annual rainfall with average maximum and lowest temperatures of 24°C and 8°C, respectively (NPBRC, Njoro Meteorological Station No.9035021, 1999). The soils are classified as well-drained, deep to extremely deep, dark reddish brown, friable and smeary, silt clay, with humic topsoil classed as mollic Andosols, with humic topsoil classified as mollic Andosols (Jaetzold & Schmidt, 2011).

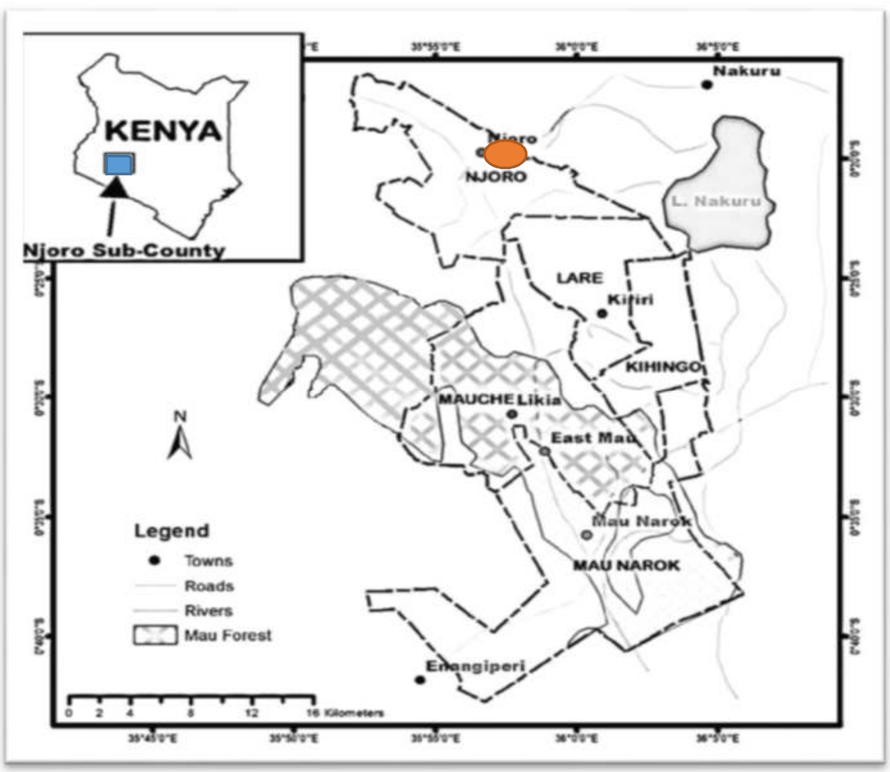


Figure 3.1: Map showing the location of the study area in Njoro Sub-County
(Source: Google map)

3.2 Treatments

Water harvesting (WH) was assigned as the main plot (Factor A) with two levels; crop rotation (CR) was the sub-plot (Factor B) with four levels; and soil fertility management (SFM) as the sub-sub plot (Factor C) with six levels. The total number of treatments were 48 treatments (4 x 2 x 6) that were replicated three times (See appendices IV, V and VI).

3.2.1 Water harvesting (WH)

Between 2014 and 2016, water harvesting (WH) as the main plot (Factor A) was tested at two levels, WH1 = Normal and WH2 = Tie ridges, for three seasons. The tie ridges in the potato crops were maintained in the same place for three seasons and were built by hand before planting, measuring 0.5 meters inside a 3-meter furrow. Tie ridges were constructed as basins surrounding the plots planted with legumes and continuous wheat (CR1, CR2 and CR4) in the crop rotation (CR1, CR2, CR3), whereas ridges were established and tied between the rows of potato crop in the plots planted with potato. During weeding, the tie ridges in the potato patches were maintained even further.

3.2.2 Crop rotation (CR)

Wheat (*Triticum aestivum* L.) (Variety=Duma), Dolichos lablab (*Lablab purpureus*) (Variety = DL1002), Green pea (Variety = Ambassador), and potato (Variety = Shangi) were planted in three-year rotation cycles as a sub-plot (Factor B) (consisting of four crop cycles). The details of crop rotation cycles were as follows: CR1 = Wheat – Dolichos – Wheat; CR2 = Wheat – Green pea – Wheat; CR3 = Wheat – Potato – Wheat; and CR4 = Continuous wheat. Wheat was grown in all plots in the first and final years of the cropping cycle (2014 and 2016, respectively) to stabilize soil fertility in the first year and to determine the cumulative effect of soil treatments in the final year and WH techniques on wheat NUE, NU_pE, NU_tE, and WUE. Crop rotation in 2015, on the other hand, with all three crops (*L. purpureus, P. sativum,* and *T. aestivum*) coming after wheat in 2014 and before wheat in 2016.

3.2.3 Soil Fertility Management (SFM)

Six different SFM strategies were used: (i) untreated control; ii) farm yard manure (FYM) (using dried cow dung) at 5 tonnes ha^{-1}; iii) green manure (GM) of an agro-forestry tree

(*Leuceana trichandra*) at 2.5 tonnes ha^{-1} on dry matter basis, which was determined after drying for three days the shredded biomass under shelter; v) inorganic fertilizer at 25 kg N ha^{-1}. During planting, phosphorus was applied blanket in all plots, except in the untreated control, at a rate of 125 kg P_2O_5 ha^{-1} in the form of rock phosphate.

Every season, biomass of *L. trichandra* was gathered at the Kenya Forestry Research Institute (KEFRI) plantation in Muguga. Fresh biomass was put into gunny bags and weighed on a scale balance right away. The biomass was then transferred to KALRO Njoro, where it was shredded using a tractor-mounted shredder while still green. Six kilograms of shredded biomass were weighed in bags, dried in the shade for three days, and then scattered equally in the furrow or uniformly throughout the plot a day before planting, depending on the WH method and crops to be planted. To prevent N volatilization, the biomass was immediately covered with a thin layer of soil following application.

3.3 Land preparation and establishment of the experiment

3.3.1 Land preparation

Primary tillage was done with a chisel plow, while secondary tillage was done twice using a disc harrow. Hand-made furrows were used to take care of WH methods, particularly the tie ridges. Regardless of the crop, the tie ridges were built by hand after planting.

The experiment was laid out using a right angle method, with the blocks marked out with wooden pegs and the end of plots inside the replicates and blocks indicated with a strip of saw dust. The thin line of sawdust was used to enable for accuracy when planting wheat and dolichos with the tractor-mounted plot seeder. Before planting potatoes, shredded *L. trichandra* biomass was sprinkled over the furrows. The shredded biomass was distributed on the field and worked in using rakes in the cases of wheat, dolichos, and green pea.

3.3.2 Establishment of the experiment

Wheat was planted on plots measuring 4.5 m x 3 m, with rows spaced 0.20 m apart and planter drilled in the rows. The plots had 23 rows of wheat, each measuring 3 meters in length. An 8-row plot seeder was used to sow the seeds. Similarly, *L. purpureus* was planted in plots of 4.5 m × 3 m, with 0.50 m between rows and 0.25 m between plants within each row. This resulted in nine rows, each with 12 holes (plants). Three seeds were planted in each hole, with one of the plants being trimmed fourteen days following emergence.

Water harvesting (WH) techniques in the shape of tie or flat plots were built, taking into account the seedbed requirements for the test crops. After sowing the crops, the tie ridges were built by hand at a one-metre interval within the regular ridges. There were no buildings on flat beds, thus it was a typical field with free flowing water. The TR were removed during the next season's field preparation to allow unrestricted movement of machinery and minimize soil compaction. Throughout the research period in both seasons, the TRs were kept in the same location and layout.

3.4 Management of the field experiment

Weed, insect pest, and disease control were all handled using standard crop management techniques. Buctril MC (Bromoxynil Octanoate 225g/1 and MCPA Ethyl Hexyl Ester 225g/1) was used to suppress broadleaved weeds on wheat plots using a knapsack sprayer at 1.5 L ha^{-1} at the 4-6 leaf stage. Weeds were managed manually in potato and the two legumes (*L. purpureus* and *P. sativum*). Hand weeding was used to suppress weeds after two weeks following emergence, while also earthing the potato crop. Folicur 250WP (Tebuconazole 0.431375 kg/litre equivalent to 3.60 lbs/gal) at 100 ml in 20 L of water was used to control fungal diseases in wheat, while Ridomil Gold 480 SL (MetalaxylM and Sisomers) at 100 ml in 20 L of water was used to control insect pests in potatoes and legumes, and Thunder OD145 (Imidacloprid 100 g/L.

3.5 Data Collection

3.5.1 Growth parameters

The growth parameters of test crops *T. aestivum, L. Purpureus,* and *P. sativum* were recorded. Germination count, number of tillers, days to heading, days to flowering, days to physiological maturity, number of spikes m^{-2}, number of seeds $spike^{-2}$, and thousand kernel weight (TKW) were among the variables recorded.Crop biomass at harvest, number of pods/plant (*L. purpureus*), number of seeds/pod, and N content on wheat grain and straw were among the other data collected.

3.5.2 Measurements of parameters on wheat (*Triticum sativum*)

A m^2 quadrat was used to collect data on the number of tillers four weeks following emergence. The number of tillers per plant was estimated using the number of seedlings per metre square. A m^2 quadrat was also used to determine the number of spikes at physiological maturity. Within each plot, the quadrat was put at two random locations. All of the plants in the quadrat were counted, and the number of spikes was tallied, then the two quadrat samples were averaged.

Ten plants were chosen from those used to calculate the number of spikes to determine the number of seeds $spike^{-2}$. Ten spikes were chosen, threshed, and the quantity of grains tallied from each spike. Finally, the number of grains per plant was calculated by dividing the total number of grains by the number of plants. Thousand kernels were weighed and the grams per 1000 seeds/kernels were calculated. Harvesting was done by sickles on the middle 18 rows by 3 m long and wheat grain yield converted to 12.5 percent moisture content.

3.5.3 Measurement of parameters on green pea (*Pisum sativum*) and Dolichos labalab (*Lablab purpureus)*

Two weeks following emergence, germination counts on *P. sativum* and *L. purpureus* were recorded using a m^2 quadrat at two randomly selected spots in each plot. The counts were averaged and the number of seedlings per m^2 was determined. On the two crop species, other variables were the number of days till flowering and physiological maturity based on reaching 50% of the stage over the entire plot. The data on the dates between emergence and physiological maturity stages of *P. sativum* and *L. purpureus* were utilized to create a table that converted dates into days from emergence. In each plot, the number of pods per plant was counted on 50 plants at random. The number of seeds per pod from the same plants was also counted. Grain yield and above-ground biomass were measured in a net plot area spanning the 6 center rows measuring 2 m. The experimental materials were uprooted from *P. sativum* and *L. purpureus* plots, weighed right away, and then sun dried for three days to decrease moisture before being recorded. The seed was removed by hand thereafter it was weighed for grain yield determination after drying the material and taking the final biomass weight. Grain yield was adjusted to a standard moisture content of 12.5 percent using the formula: Grain yield at 12.5 percent = Plot grain yield * (100 –

actual grain moisture)/ (100 – 12.5 percent). *P. sativum* and *L. purpureus* grain yields were extrapolated to a unit of tonnes ha^{-1}.

3.5.4 Measurements of parameters on potato (*Solanum tuberosum*)

S. tuberosum plots were 4.5 m x 3 m, with 7 rows 0.75 m apart and 0.3 m (10 plants per row) between plants inside each row. Two rows on both ends of the plots functioned as guard rows and were utilized for destructive sampling, while 0.5 m on both ends of the plots also served as guard rows and were not collected for determining potato yields.

Several characteristics were measured in the plots, including percent emergence, above-ground biomass, and tuber yield. After two weeks of emergence, the crop emergence rate of S. tuberosum was measured manually by counting all the emerging plants on a plot of 4.5 m × 3 m randomly selected places in each plot using a m^2 quadrat. The counts were averaged and the number of seedlings per m^2 was determined. On the basis of reaching 50% of the stage, the number of days to heading, flowering, and physiological maturity were recorded. The dates between emergence and physiological maturity stages of several crops were utilized to create a table that could be used to translate dates into days since emergence.

By sampling from the outside rows of a metre length, above ground biomass was determined at 50% physiological maturity. The crop material was sun dried first, then oven dried at 70°C until it reached a consistent weight, and the final weight was stated in kg m2. Harvesting net plots with 6 rows and a length of 2 meters were used to evaluate potato tuber production and above ground biomass.

3.5.5 Determination of soil moisture and temperature

Between 8 and 10 a.m., soil moisture and temperatures were monitored with a Time Domain Reflectance (TDR) meter to a depth of 16 mm in four pre-determined places in each plot of all the test crops. Time-Domain-Reflectometry TDR measured soil moisture in terms of volumetric water content, whereas soil temperature was measured in degrees Celsius (ºC).

Detailed meteorological records of daily rainfall and its distribution during the growing season were essential data for measuring water consumption. A TDR 300 (TRIME PICO64; IMKO Micromodultechnik GmbH, Ettlingen, Germany) soil moisture meter was used to measure soil moisture content at a depth of 160 mm at four randomly selected places within each plot on a weekly basis. With an accuracy of 1 pico-second of a radar trip time, this device assessed % soil moisture content, temperature (ºC), and electrical conductivity (dS/m).

3.5.6 Determination of Nitrogen Use Efficiency (NUE) and its components, Nitrogen Uptake Efficiency (NU_pE) and Nitrogen Utilization Efficiency (NU_tE)

The nitrogen use efficiency (NUE) was calculated on the basis of NU_tE at the end of the third wheat-growing season. Plant samples obtained after harvest (wheat plots) were sorted into grain and straw, then oven-dried for 48 hours at 70°C to achieve a constant weight. Dry grain and straw samples were milled to 1 mm using chromium balls in a Retsch mill (model:mm400), and the flour was then placed in test cells for nitrogen measurement using a FOSS Near Infrared model Infratec 1241 Grain Analyzer (American Association of Cereal Chemists, 2000). In the laboratory at the Kenya Agricultural and Livestock Research Organization (KALRO) Njoro, milled samples were tested for total N content using a Near Infrared Reflectance (NIR) analyzer for grain and flour quality characteristics. Various reliable formulas were used to assess nitrogen usage efficiency (NUE) and its related characteristics in this study.

Biomass and grain nitrogen content were utilized to calculate NUE in wheat in this work, therefore NUE was calculated according to Delogu *et al.* (1998) and López-Bellido & López-Bellido (2001). However, because the nitrogen content was calculated from protein content using method by Halvorson *et al.*(2004):

$$\text{N content} = \frac{\text{protein content (\%)}}{5.7} \qquad [3]$$

The equations below were used to calculate other key NUE characteristics such as nitrogen uptake efficiency (NU_pE) and nitrogen utilization efficiency (NU_tE):

$$\text{Nitrogen uptake efficiency } (NU_pE, \text{ kg kg}^{-1}) = N_t / N_{supply} \qquad [4]$$

N_t stands for total plant N uptake in kg ha^{-1}, which was calculated by multiplying the dry weight of plant parts by the N concentration of the plant samples and adding the results to get the total absorption. The sum of soil N content at sowing, mineralized N, and N-uptake in control is N_{supply} (0 N applied). According to Limon-Ortega *et al.* (2000), nitrogen (N) supply fertilizer was calculated as the sum of (i) N applied as fertilizer and (ii) total N absorption in the control (0 N application).

Because of their relevance in demonstrating the effectiveness of the crop in getting N (applied and native) from the soil, nitrogen uptake efficiency (NU_pE) and nitrogen utilization efficiency (NU_tE) were also calculated in this study. For example Raun and Johnson (1999) utilized NU_tE as a technique to boost NUE, and it was calculated using the formula below:

Nitrogen utilization efficiency (NU_tE, kg kg^{-1}) = G_y / N_t [5]

Where G_y depicts grain yield in kilograms per hectare, and N_t is total plant nitrogen absorption in kilograms per hectare, calculated by multiplying the dry weight of plant parts by the nitrogen concentration and summing the parts for total uptake.

Nitrogen use efficiency (NUE, kg kg^{-1}) = G_y / N_{supply} [6]

Where G_y depicts grain yield in kilograms per hectare, and N_{supply} is the sum of soil N content at sowing, mineralized N, and N-uptake in the control (0 N applied) in kilograms per hectare.

3.5.7 Determination of Water Use Efficiency (WUE)

Water Use Efficiency (WUE) was calculated by first calculating water use (WU) using the following formula established by French and Schultz (1984):

Water use (WU) (mm) = (soil water at planting (mm) – soil water at maturity (mm) + in-season crop rainfall (mm) (rainfall during the crop season).

Thus, grain production (kg/ha) was divided by the mean of three seasons total water consumption (ET) to calculate water-use efficiency (WUE):

WUE (kg/ha.mm) = grain yield (Y)/mean water-use (ET) [7]

Where Y is the yield in kg ha^{-1} and ET is Evaporation transpiration.

3.6 Soil sampling and preparation

A soil auger was used to gather soil samples at the start of each season of the experiment. Satellite soil samples were taken at different spots around the area with depths of 0-15 and 15–30 cm at the start of the experiment. The samples from depths of 0-15 and 15–30 cm were bulked and sub-samples were collected from each. The original soil analysis findings were utilized as a benchmark for the field's soil fertility condition. To evaluate micro and macro nutrients, soil samples were taken from each plot at the end of each season up to a depth of 0 -30 cm.

Soil samples were processed for examination by first sun drying them and then placing them on plastic plates in the laboratory, where they were crushed with a mortar and pestle. Before the analysis, the crushed samples were sieved with a 5-mm sieve.

3.7 Soil analysis

At the soil laboratory, soil pH, micro and macronutrients were determined using the procedures published by Okalebo *et al*. (2002). Total N, P, K, Ca, Mg, Mn, Zn, Cu, Fe, %N and %C were among the macro and micronutrients studied. However, this thesis only reported the procedures for the determination of total N, P, and organic carbon.

3.7.1 General extraction

The nutrients were extracted using the Mehlic Double Acid technique, which involved mixing 2M HCl and 0.0125 M H_2SO_4 in a 1:5 soil:volume ratio (w/v) combination (Mehlich, 1984).

3.7.2 Determination of soil reaction (pH)

A soil suspension was made with distilled water at a 1:2 soil-to-water ratio, and the concentration of hydrogen ions in the suspension (pH) was determined using a potentiometric technique (Jackson, 1973). The pH of the solution was determined using a saturated calomel electrode as a reference electrode, which is proportional to the potential produced on the glass membrane.

3.7.3 Determination of Soil Organic carbon

Anderson and Ingram (1993) devised a colorimetric technique for determining carbon content (percent) in soils. To guarantee full oxidation, the acidified dichromate was heated to 1500°C for 30 minutes. After adding the Barium Chloride to the cooled digest and properly mixing it in, the solution was allowed to sit overnight. A UV – Pharmaspec Shimadzu spectrophotometer was used to determine the concentration of C and the amount of accessible Phosphorous (P) (Anderson & Ingram, 1993).

3.7.4 Determination of Total nitrogen

Total nitrogen (N) was measured using the micro kjeldahl digestion technique, in which organic N is transformed to ammonium in the presence of H2SO4, K2SO4, and CuSO4 catalyst amino nitrogen in various organic materials (Bremner &Keeney, 1965). Free ammonia is also transformed to ammonium during this process. The ammonia was distilled from the alkaline medium and absorbed in boric acid after adding a base. Titration with a standard mineral acid (dilute H_2SO_4) was used to quantify the amount of ammonia (Okalebo *et al.,* 2002). The carbon and nitrogen content of the soils, as well as the POM and Ludox density fractions, were all measured. For soil organic C, Anderson and Ingram (1993) proposed a colorimetric technique. Following Kjeldahl digestion, total N was also measured colorimetrically (Parkinson & Allen, 1975). Chloroform fumigation for 12 hours was followed by extraction with 0.5 M K_2SO_4 to determine microbial biomass, C, and N. (Vance *et al.,* 1987). Anderson and Ingram's (1993) technique was used to colorimetrically quantify carbon in the extract.

3.7.5 Determination of Phosphorous

The extractable phosphorous (P) and exchangeable cations (Na^+, K^+, Ca^{2+}, and Mg^{2+}) were measured using the Mehlich-1 (M1) extraction technique, with P and Mg2+ assessed calorimetrically in a spectrophotometer and Ca^{2+}, K^+, and Na^+ determined using a flame photometer (Mehlich, 1984).

3.7.6 Preparation and chemical characterization of Farm Yard Manure (FYM)

Every season, farm yard manure (FYM) was gathered from the KALRO Njoro cow shed and put on canvas for one week to dry in the shade. A sub-sample of around 100 kg was fully mixed, then 20 kg was selected and thoroughly mixed once more. The final 2 kg sample was sent to KALRO Njoro's soil chemistry laboratory for examination. The material was crushed in the laboratory with a pestle and mortar before being sieved through a 5 mm sieve. The chemical composition of the substance was determined using conventional laboratory techniques, as shown in Table 3.1.

3.8 Data Analysis

Using the Genstat 15th edition statistical program, the data was subjected to an analysis of variance (ANOVA) (Genstat 5 Committee, 1993). Error (a) was used to test the main factor, whereas error (b) was used to test the sub-plot factor, and error (c) was used to test the sub-sub factor (c). Fisher's least significant difference (Lsd) was used to compare several means at 5% significance level. Tables and graphs with error bars representing standard error of the mean were used to show the findings of the study. When there was no statistical significance, trends were highlighted. Correlation analysis was also performed on the means.

Two statistical models developed by Steel and Torrie (1962) were employed in the investigation. The cumulative impacts of water harvesting (WH), crop rotation (CR), and soil fertility management (SFM) on NUE, NU_tE, NU_pE, WUE, and wheat grain yield, as well as biomass, were studied using the first (i) model. The adoption of the first model for NUE, NU_tE, NU_pE, WUE, grain yield, and biomass of wheat was justified since NUE, NU_tE, and NU_pE were calculated using the mean N over the three seasons. The mean of total water use (TWU) for the three seasons was used to calculate WUE. The means examined in the case of grain yield and biomass were from the third season. However, for the study of the impacts of WH, CR, and SFM, as well as season (S), on soil organic carbon (SOC), soil nitrogen (N), soil temperature (ST), soil moisture concentration (SMC), and TWU, the second model (ii) was employed (TWU).

Model (i) $Y_{ijkl} = \mu + \beta_i + C_j + (\beta CR)_{ij} + WH_k + (CRWH)_{jk} + (\beta CRWH)_{ijk} + SFM_l + (SFMCR)_{il} + (WHSFM)_{kl} + (CRWHSFM)_{jkl} + \epsilon_{(ijkl)}$

Where

Y_{ijkl} = Responses from the j^{th} crop rotation (CR), k^{th} water harvesting (WH) and $_l$th soil fertility management (SFM); μ = Grand mean; β_i = Effect of $_i$th block i=1, 3; CR_j = Effect of the $_j$th crop rotation j = 1, 4; βCR_{ij} = Error (A); WH_k = Effect of k^{th} water harvesting k=1, 2; $CRWH_{jk}$ = Interaction effect of the $_j$th crop rotation and the $_k$th water harvesting; $\beta CRWH_{ijk}$= Error (B); SFM_l = Effect of l^{th} Soil Fertility Management l =1, 6; $SFMCR_{jl}$= Interaction effect of the jth crop rotation and l^{th} soil fertility management; $WHSFM_{kl}$ = Interaction effect of the k^{th} water harvesting and l^{th} soil fertility management; $CRWHSFM_{jkl}$ = Interaction effect of j^{th} crop rotation, k^{th} water harvesting and the l^{th} soil fertility management; $\epsilon_{m(ij\kappa l)}$ = Error.

Model (ii) $Y_{ijklm} = \mu + \beta_i + WH_j + \beta WH_{ij} + CR_k + WHCR_{jk} + \beta WHCR_{ijk} + SFM_l + WHSFM_{jl} + WHCRSFM_{jkl} + S_m + WHS_{jm} + CRS_{km} + SFMS_{lm} + WHCRSFMS_{jklm} + \varepsilon_{ijklm}$

Where

Y_{ijklm} = Responses from the j^{th} water harvesting (WH); k^{th} crop rotation (CR) and $_l$th soil fertility management (SFM); $_m$th Season; μ = Grand mean; β_i = Effect of $_i$th block i=1,2,3; WH_j = Effect of $_j$th water harvesting (WH) $_j$=1,2; CR_k = Effect of the $_k$th crop rotation (CR) k = 1,2,3, 4; βWH_{ij} = Error (A); C_k = Effect of k^{th} Crop rotation (CR) k=1, 2,3,4; $WHCR_{jk}$ = Interaction effect of the $_j$th water harvesting and $_k$th crop rotation; $\beta WHCR_{ijk}$ = Error (B); F_l = Effect of l^{th} Soil Fertility Management (SFM) l =1,2,3,4,5,6; $WHSFM_{jl}$ = Interaction effect of the j^{th} water harvesting and l^{th} soil fertility management; $CRSFM_{kl}$ = Interaction effect of the k^{th} crop rotation and l^{th} soil fertility management; $WHCRSFM_{jkl}$ = Interaction effect of j^{th} water harvesting, k^{th} crop rotation and the l^{th} soil fertility management; $\epsilon_{m(ij\kappa lm)}$ = Error.

CHAPTER FOUR

RESULTS

4.1 Rainfall distribution during the experimental period

The rainfall levels fluctuated between the three seasons studied (I, II, and III), with 2014 and 2015 having uneven rainfall (Table 4.1). This was demonstrated by the fact that over half of the total seasonal rain fell in the first month of the trial (August 2014) following planting in 2014, and more than half of the total seasonal rain occurred in the first two months (April and May) in 2015. However, the seasonal rainfall distribution in 2016 was fair because the final four months of the season (May – August 2016) got more or equal quantities of rain. Season III got 1048.1 mm of rain, which was greater than season I (839.4 mm) and season II (839.4 mm) (572.2 mm). Seasons I and III had better rainfall distribution than season II, which had nearly 66 percent of the growing season's rainfall fall in April and May. (Table 4.1). The yearly rainfall in the third season was roughly 15% greater than in seasons I and II.

Table 4.1: Seasonal and annual rainfall at KALRO Njoro during the study periods between 2014 and 2016

	2014			2015			2016		
Month	**Rainfall (mm)**	**% of rainfall during trial season I**	**% of Annual rainfall**	**Rainfall (mm)**	**% of rainfall during trial season II**	**% of Annual rainfall**	**Rainfall (mm)**	**% of rainfall during trial season II**	**% of Annual rainfall**
January	9.4	-	1.12	1.00	-	0.11	70.2	-	6.70
February	30.9	-	3.68	13.9	-	1.56	15.8	-	1.51
March	80.7	-	9.61	16.1	-	1.80	44.4	-	4.24
April	61.5	-	7.33	**168.2**	29.40	18.82	234	33.79	22.33
May	102.3	-	12.19	**213.4**	37.29	23.88	125.7	18.15	11.99
June	96.4	-	11.48	**83.0**	14.51	9.29	105.5	15.23	10.07
July	85.6	-	10.20	**54.5**	9.52	6.10	98.8	14.27	9.43
August	**160.4**	48.12	19.11	**53.1**	9.28	5.94	128.5	18.56	12.26
September	**50.2**	15.06	5.98	67.1	-	7.51	105.9	-	10.10
October	**74.2**	22.26	8.84	66.8	-	7.47	65.8	-	6.28
November	**48.5**	14.55	5.78	117.4	-	13.13	48.8	-	4.66
December	**39.3**	-	4.68	39.3	-	4.40	4.7	-	0.45
Total for the trial period	333.3	100.00		572.2	100.00	-	692.5	100.00	-
Annual Total	839.4	-	100.00	893.8	-	100.00	1048.1	-	100

4.2 Chemical characterization of Farm yard manure (FYM) and *Leuceana trichandra* biomass

Table 4.2 displays the chemical properties of farm yard manure (FYM) and *L. trichandra.* The average results in Table 3.1 demonstrate that P was less than sufficient in both FYM and *L. trichandra* samples when compared to essential levels. Other elements, such as carbon and nitrogen (N), were over the crucial threshold. In samples from FYM (6.31%) and Leuceana (7.57%), the value of C is more than twice the mean of the crucial level (2–4%) range. Both samples had N values of nearly four times the threshold level (FYM = 1.01 percent; Leuceana = 0.99) (0.25%).

Table 4.2: Chemical composition of farm yard manure (FYM) and *L. trichandra*

Material	pH	C (%)	N (%)	P (mg/kg)
Farm yard manure	8.37	6.31	1.01	**0.4620**
Leuceana spp	-	7.57	0.99	**0.3023**
Critical level	5.5 – 6.5	2 – 4	0.25	35

Key: Bolded and underlined figures depict deficiency

4.3 Mean squares showing the effects of pre-crops in Crop rotation - CR, water harvesting (WH) and soil fertility management (SFM); and their interactions on soil nitrogen (SN), soil organic carbon (SOC), soil moisture (SM), soil temperature (ST) and total water use (TWU)

The mean squares of the effects of water harvesting (WH), crop rotation (CR), soil fertility management (SFM), and season (S) on soil organic carbon (SOC), soil nitrogen (SN), soil moisture (SM), soil temperature (ST), and total water use (TWU), as well as their interactions are presented in Table 4.3. Crop rotation (CR) had a significant ($p < 0.001$) main factor effect on SM, ST, and TWU, whereas season (S) influenced SOC, SN, SM, ST, and TWU. On SOC, as well as ST and TWU, significant two-way interactions of WH x S and CR x S were observed.

Table 4.3: Mean squares showing the effects of pre-crops (Crop rotation - CR), water harvesting (WH) and soil fertility management (SFM); and their interactions on soil N, soil organic carbon (SOC), soil moisture, soil temperature and total water use (TWU)

Source of variation	Df	Soil organic carbon	Soil N	Soil Temperature	Soil moisture	Total water use
Rep	2	9.0713	0.08467	296.876	7165	0.7198
Water harvesting (WH)	1	2.7333	0.00027	7.358	117.5	0.0166
Residual	2	1.3202	0.07959	9.567	181.3	0.0245
Crop rotation (CR)	3	0.1952	0.0071	165.176***	2885.5***	0.2783***
WH x CR	3	0.0151	0.01031	1.38	128.4	0.0119
Residual	12	0.3157	0.01062	2.065	198.3	0.0176
Soil Fertility Management (SFM)	5	0.0226	0.02539	2.848	141.2	0.0120
WH x SFM	5	0.0863	0.01371	1.086	49.1	0.0044
CR x SFM	15	0.1443	0.01695	1.721	205.4	0.0181
WH x CR x SFM	15	0.1918	0.01338	3.426*	269.2	0.0224
Residual	80	0.4451	0.01282	1.601	232.3	0.0204
Season (S)	2	38.4003***	6.39154***	100.526***	98341.2***	1235000***
WH x S	2	8.08***	0.00097	1.068	69	0.0049
CR x S	6	0.2337	0.01166	156.102***	954.7***	0.08588***
SFM x S	10	0.329	0.02054	1.495	192.6	0.0171
WH x CR x S	6	0.2786	0.02334	0.806	20.3	0.0012
WH x SFM x S	10	0.1336	0.00976	1.346	105	0.0084
CR x SFM x S	30	0.246	0.00975	0.543	102.6	0.0079
WH x CR x SFM x S	30	0.2262	0.01291	0.805	103.6	0.0077
Residual	192	0.6928	0.01273	2.185	179.1	0.0157
Total	431					

Key: * - $p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

4.4 Effect of interaction between water harvesting (WH) and season (S) on soil organic carbon (SOC)

In Figure 4.1, the effects of the interaction between water harvesting (WH) and season (S) on soil organic carbon (SOC) are presented. The combination between water harvesting and season had a substantial ($p < 0.001$) impact on soil organic carbon (SOC). The value of SOC was much higher in the first season than in the second and third seasons. Soil organic carbon (SOC) was substantially higher under tie ridges than flatbed during the first and second seasons, while larger values were found under flatbed in the third season. The high SOC value recorded during the first cropping season might be ascribed to the fact that it came after a four-year fallow period.

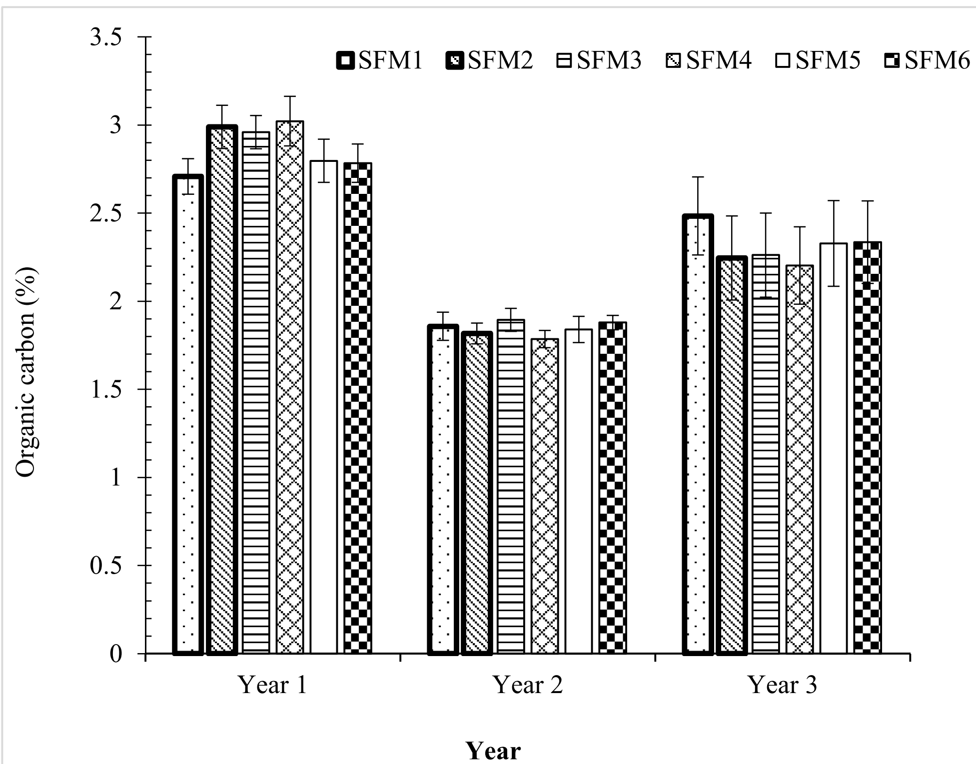


Figure 4.1: Effect of interaction between water harvesting (WH) and season on soil organic carbon (SOC)

Key: SFM1 = untreated control; SFM2 = Farm yard manure (FYM) at 5 tonnes/ha; SFM3 = green manure (*L. trichandra*); SFM4 = inorganic N source at 25 kg N/ha; SFM5 = inorganic source at 50 kg N/ha; SFM6 = inorganic source at 75 kg N/ha.

4.5 Effect of interaction between crop rotation (CR) and season on soil temperature

In Figure 4.2, the effects of the interaction between crop rotation (CR) and season (S) on soil temperature (ST) are shown. Because of the interplay between CR and season, there were no significant impacts on soil temperature.

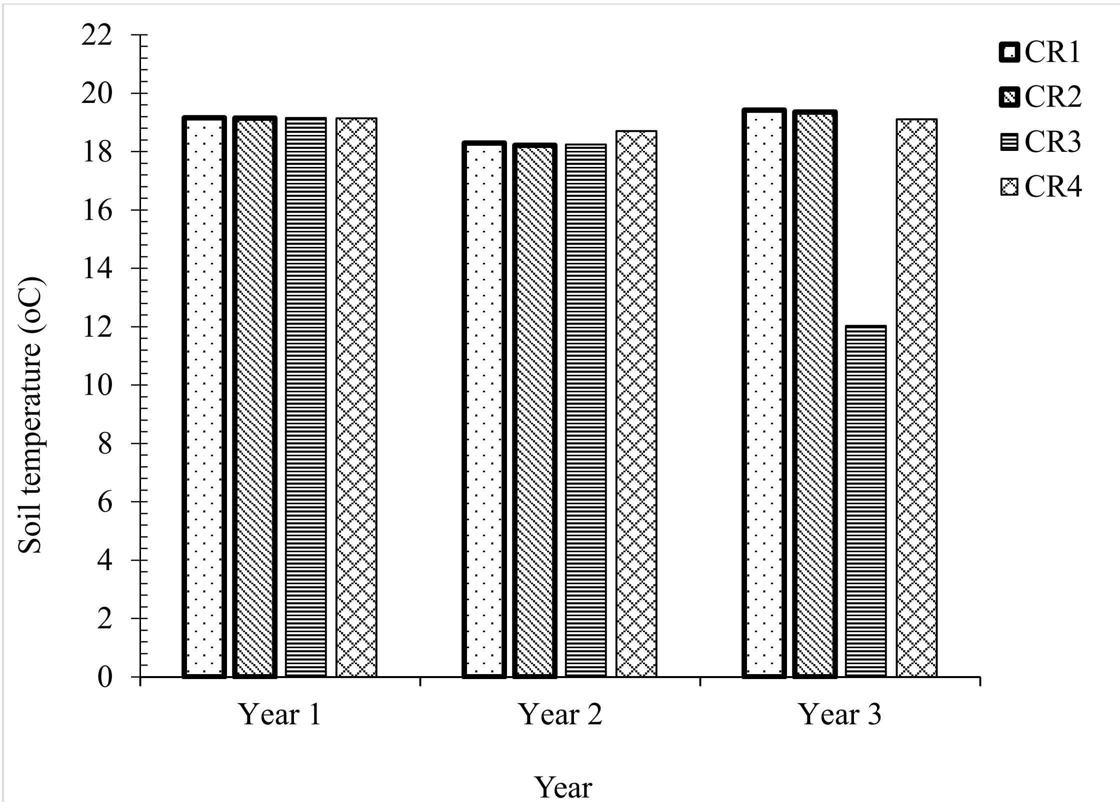


Figure 4.2: Effect of interaction between crop rotation (CR) and season on soil temperature

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat.

4.6 Effect of interaction between crop rotation (CR) and season on total water use (TWU)

Figure 4.3 shows the influence of crop rotation (CR) and season (S) interactions on total water usage (TWU). The interaction between CR and S had a substantial ($p < 0.001$) impact on total water usage. TWU values were higher in the second and third seasons than in the first season. Interactions between CR and seasons two and three resulted in no significant changes in TWU values. The significant seasonal and yearly rainfall during the second and third seasons may have contributed to this.

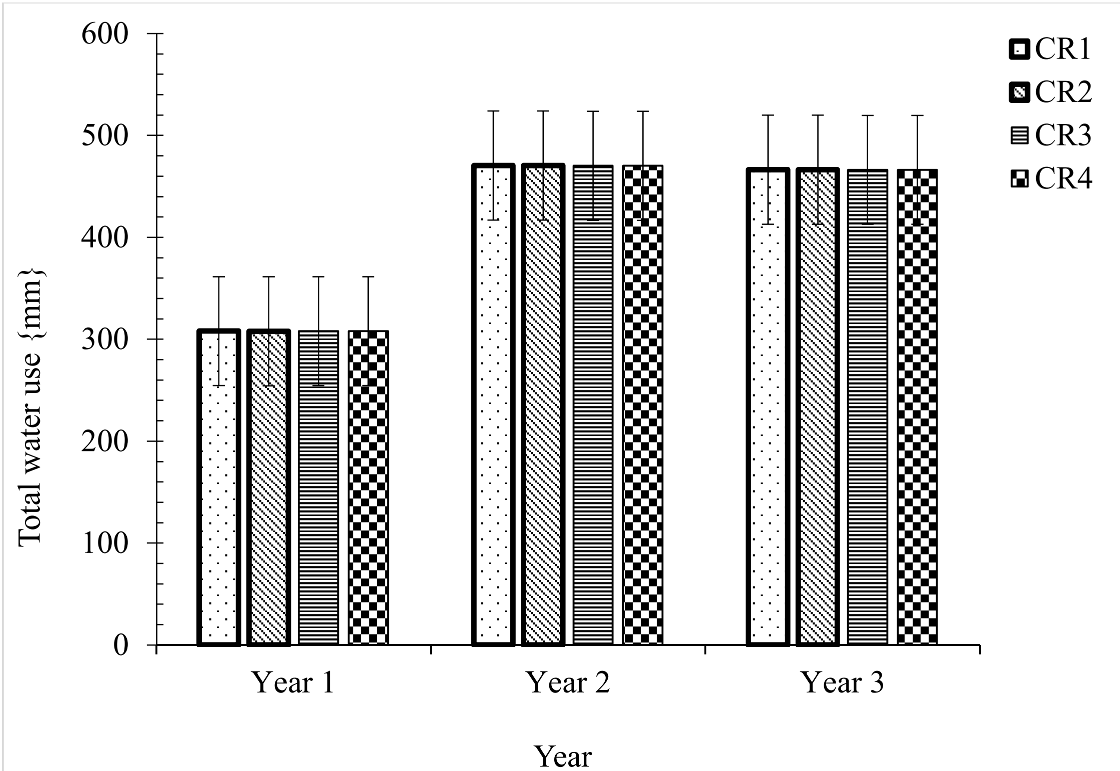


Figure 4.3: Effect of interaction between crop rotation (CR) and season on total water use (TWU)

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat.

4.7 Effect of interaction between crop rotation (CR) and season (S) on soil nitrogen

The findings of the crop rotation (CR) and season (S) interaction effects are presented in Figure 4.4. Because of the interplay between crop rotation (CR) and season, no significant influence on soil N was detected (S). This meant that the value of soil N did not change with the seasons. The first season, on the other hand, had higher soil N levels than the second and third seasons. The high levels of soil N found in the first season are due to the fact that the site had been fallow for four seasons, allowing it to collect greater levels of native nitrogen.

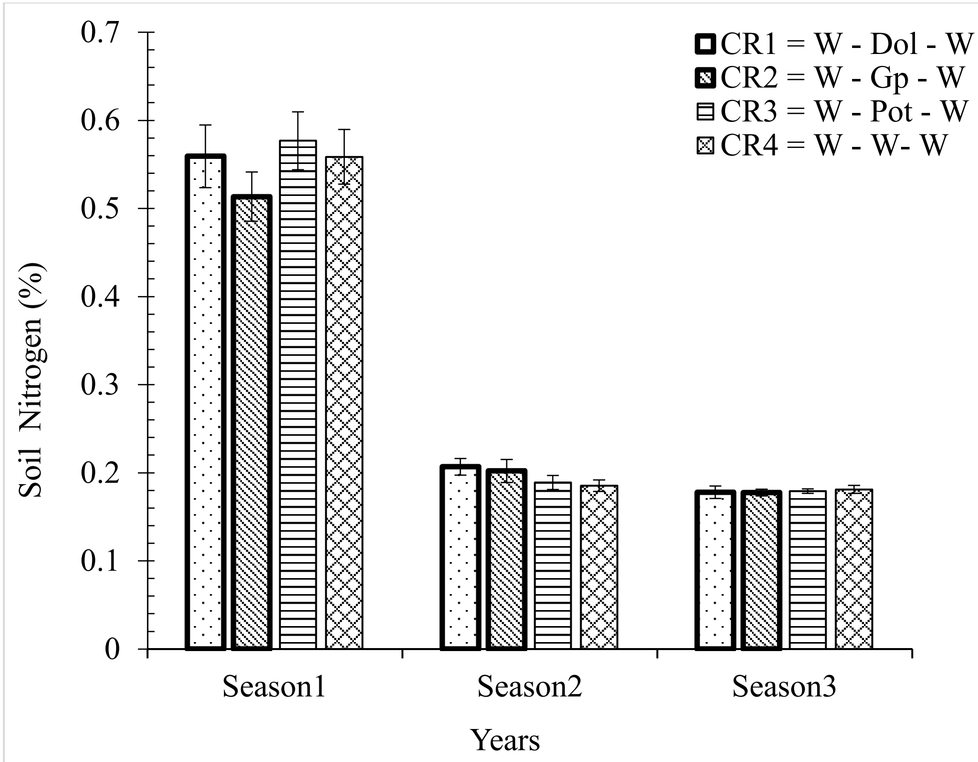


Figure 4.4: Effect of interaction between crop rotation and season on soil nitrogen.

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat

4.8 Effect of interaction between crop rotation (CR) and season (S) on soil moisture

The results that depict the impact of crop rotation (CR) and season (S) interactions on soil moisture concentration (SMC) are presented in Table 4.5. A relationship between CR and S significantly ($p < 0.05$) impacted soil moisture concentration (SMC). In the first and second seasons, the soil moisture content (SMC) was significantly higher than in the third. CR1 (W – Dol – W) and CR2 (W – Gp – W) had substantially higher SMC values than CR3 (W – Pot – W) and CR4 (W – W- W) in the first season, whereas CR3 (W – Pot – W) and CR4 (W – W- W) had significantly lower SMC values in the second season.

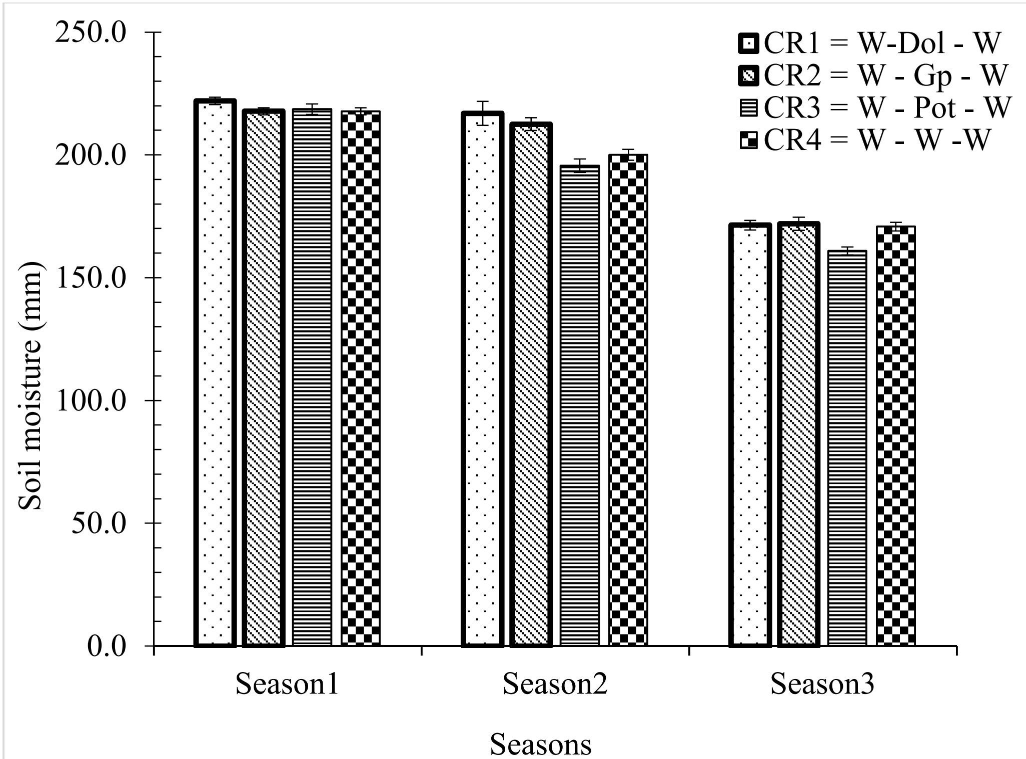


Figure 4.5: Effect of interaction between crop rotation (CR) and season (S) on soil moisture

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat

4.9 Effect of interaction between soil fertility management and season on soil moisture concentration

Figure 4.6 illustrates the findings of the interaction between soil fertility management (SFM) and season (S) on soil moisture concentration (SMC). Soil moisture concentration (SMC) was not significantly affected by the interaction between SFM and S. Although an interaction between SFM and S had no effect on SMC, there was a trend in the first and second seasons for higher SMC values than in the third season. There were no variations in SMC value across all SFM strategies in the first season, however in the second season, SFM4 (inorganic source @25 kg N ha^{-1}) had the highest SMC value compared to the other SFM methods examined. SFM5 (inorganic source at 50 kg N ha^{-1}) had higher SMC than the other SFM methods tested during the third season. When looking over specific seasons, it was discovered that inorganic sources of N accumulated more SMC.

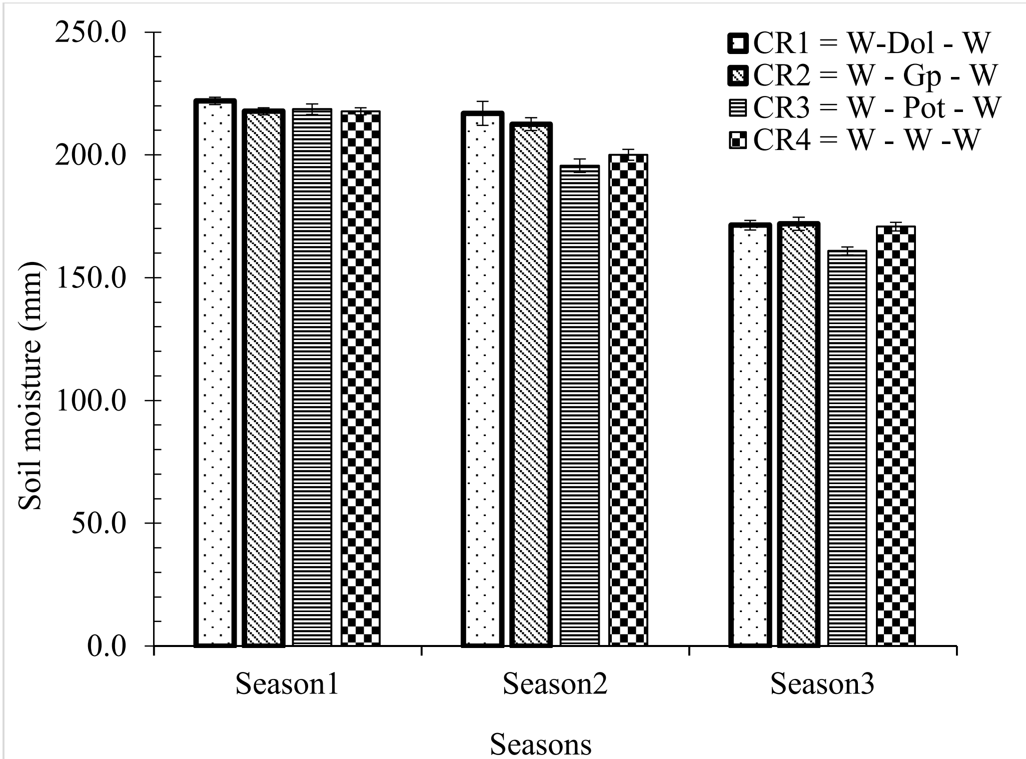


Figure 4.6: Effect of interaction between soil fertility management (SFM) and season (S) on soil moisture concentration

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat.

4.10 Effect of interaction between soil fertility management and season on soil nitrogen

Figure 4.7 demonstrates the effects of the interaction between soil fertility management (SFM) and season (S) on soil nitrogen levels. Soil N was not affected by the interaction of SFM and S. Despite this, soil N was found to be higher in the first season than in the second and third seasons. During the first season, SFM3 (green manure utilizing *L. trichandra* at 2.5 tonnes ha^{-1}) produced the highest value of soil N, with no difference in the value of soil N owing to the other SFM methods examined. Soil N levels were likewise somewhat higher in the second season than in the third.

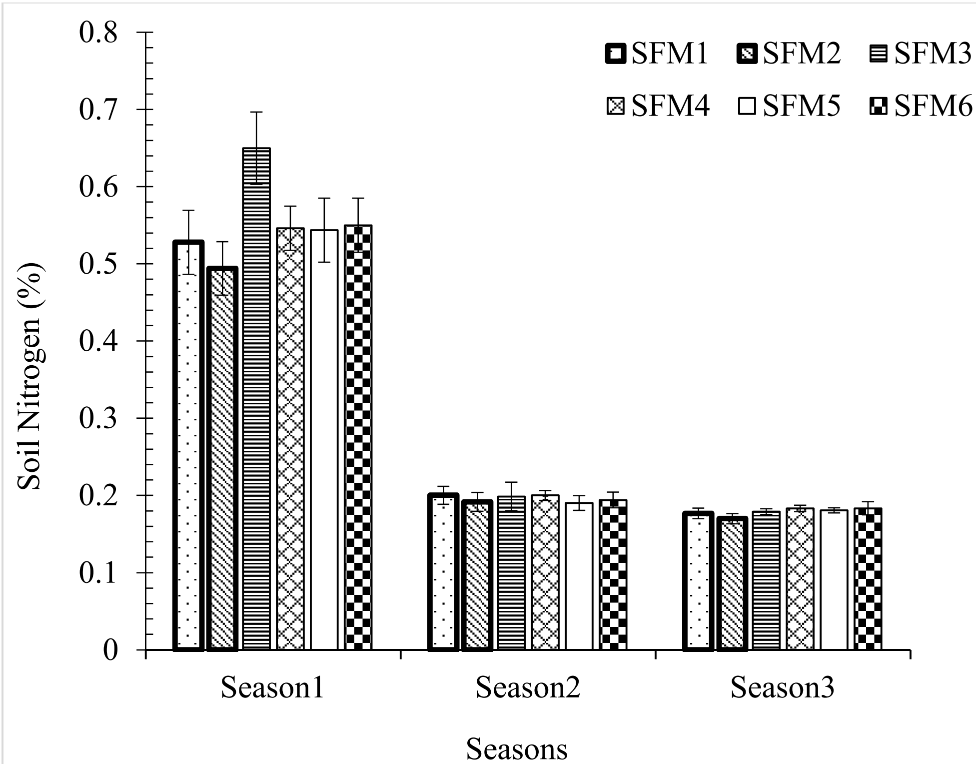


Figure 4.7: Interaction effect of soil fertility management and season on soil nitrogen.

Key: SFM1 = untreated control; SFM2 = Farm yard manure (FYM) at 5 tonnes/ha; SFM3 = green manure (*L. trichandra*); SFM4 = inorganic N source at 25 kg N/ha; SFM5 = inorganic source at 50 kg N/ha; SFM6 = inorganic source at 75 kg N/ha.

4.11 Mean squares showing the cumulative effects of crop rotation (CR), water harvesting (WH), soil fertility management (SFM) and their interactions on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NU_tE), nitrogen uptake efficiency (NU_pE) of wheat

Table 4.4 illustrates the overall effect of crop rotation (CR), water harvesting (WH), and soil fertility management (SFM) on NUE, NU_tE, NU_pE, WUE, grain yield, and biomass of wheat, as well as their interactions. All of the variables studied had a significant ($p < 0.005$) main effect owing to CR, whereas SFM influenced all of them except NU_tE and biomass. All of the factors measured throughout the experiment had no significant ($p > 0.05$) influence on water harvesting (WH). The interaction between WH x CR and WH x SFM showed substantial impacts on WUE and grain yield in both directions, whereas the interaction between CR and SFM had significant effects on all of the variables except NU_tE.

Table 4.4: Mean squares showing the effects of crop rotation (CR), water harvesting (WH), soil fertility management (SFM) and their interactions on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NU_tE), nitrogen uptake efficiency (NU_pE)

Source of variation	d.f.	NUE	NU_tE	NU_pE
Rep stratum	2	272.3	78.89	261.4
Water harvesting (WH)	1	301.2	71.46	461.8
Residual	6	82.3	15.41	129.8
Crop rotation (CR)	3	2723.5***	791.37***	3631.6***
CR x WH	3	259.6	33.41	598.8
Residual	8	169.8	36.55	169
Soil fertility management (SFM)	5	1182.3***	11.2	1495.2***
CR x SFM	15	591.8***	11.33	1130.4***
WH x SFM	5	168.1	17.14	234.2
CR x WH x SFM	15	144.9	7.95	366.2
Residual	80	146	19.27	234.7
Total	143			

Key *-$p < 0.05$; ** - $p < 0.01$; *** - $p < 0.001$

4.12 Cumulative effect of water harvesting (WH) on Nitrogen use efficiency (NUE). Nitrogen utilization efficiency (NU_tE) and Nitrogen uptake efficiency (NU_pE) of wheat

Figures 4.8, 4.9, and 4.10 show the effects of several water harvesting (WH) techniques on NUE, NU_tE, and NU_pE, respectively. The results showed that water harvesting (WH) had no significant impact on wheat NUE, NU_tE, or NU_pE. Although there were no significant changes in the value of NUE, NU_tE, and NU_pE between growing wheat beneath flat and tie ridges. This shown that tie ridges might be beneficial in improving the efficiency of N usage, as well as its absorption and total utilization for increased crop yield.

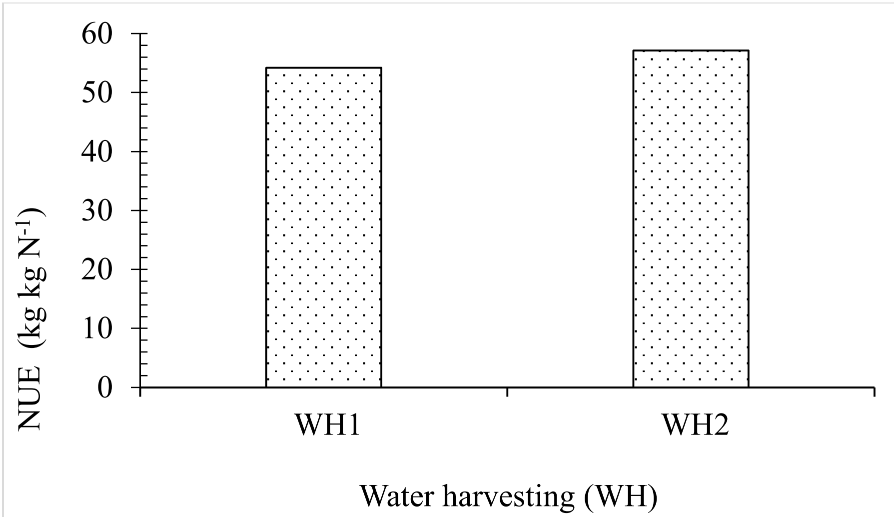


Figure 4.8: Effect of water harvesting (WH) on NUE

Key: WH1 = Flat beds; WH2 = Tie ridges

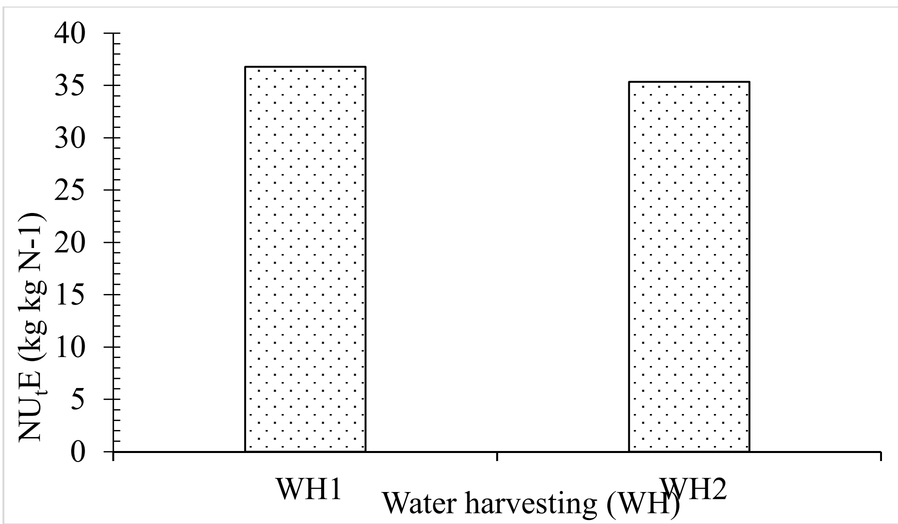


Figure 4.9: Effect of water harvesting (WH) on NU_tE.

Key: WH1 = Flat beds; WH2 = Tie ridges.

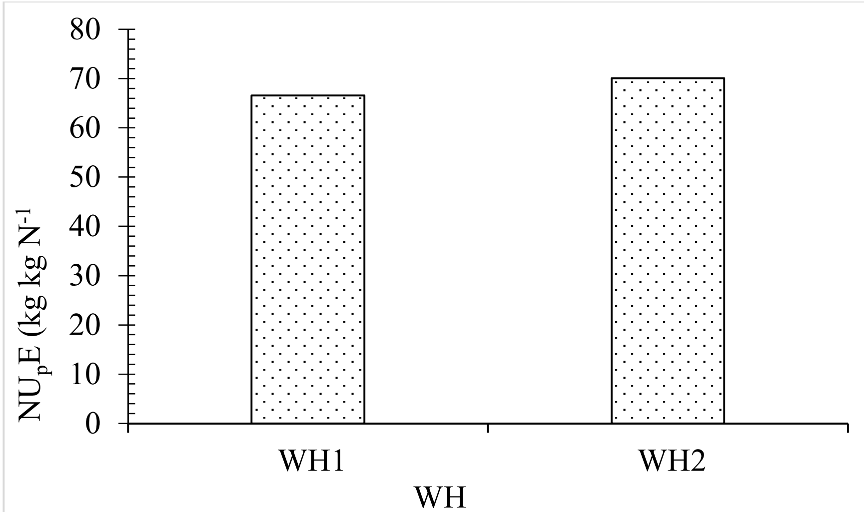


Figure 4.10: Effect of water harvesting (WH) on NU_pE.

Key: WH1 = Flat beds; WH2 = Tie ridges.

4.13 Mean squares showing the cumulative effect of crop rotation (CR), water harvesting (WH), soil fertility management (SFM) and their interactions on water use efficiency (WUE), yield and biomass of wheat

The mean squares tables illustrating the influence of CR, WH, and SFM on water use efficiency (WUE), yield, and biomass are presented in Table 4.5. Water use efficiency (WUE), yield, and biomass were strongly influenced ($p < 0.001$) by the major variables of CR and SFM. SFM, on the other hand, had a substantial ($p < 0.001$) influence on WUE and yield, but had no effect on biomass. On both WUE and yield, significant interaction effects involving CR and SFM, as well as WH and SFM, were detected, but no effect on biomass. Water use efficiency (WUE) and yield were also affected by a three-way interaction involving CR, WH, and SFM.

Table 4.5: Mean squares showing the cumulative effects of crop rotation (CR), water harvesting (WH), soil fertility management (SFM) and their interactions on water use efficiency (WUE), grain yield and biomass

Source of variation	d.f.	WUE	Grain yield	Biomass
Rep stratum	2	2.1486	170559	1011567
Water harvesting (WH)	1	0.217	68885	3023230
Residual	6	0.1535	96637	2486833
Crop rotation (CR)	3	8.8991***	4043216***	278282147***
CR x WH	3	5.6175**	1405269***	327497
Residual	8	0.564	83443	884697
Soil fertility management (SFM)	5	8.3332***	2084977***	1455007
CR x SFM	15	8.3332***	414976***	1138137
WH x SFM	5	8.3332***	516217***	564371
CR x WH x SFM	15	8.3332***	191432***	1583192
Residual	80	8.3332	48198	922779
Total	143			

Key *-p < 0.05; ** - p < 0.01; *** - p < 0.001

4.14 Effect of water harvesting on water use efficiency (WUE) of wheat

The effects of water harvesting (WH) on WUE were not substantial, according to the findings (Figure 4.11). The lack of effect of WH on WUE might be ascribed to the fact that moisture was not a limiting factor throughout the three seasons (2014–2016) because rainfall was enough for the crops utilized in the experiment.

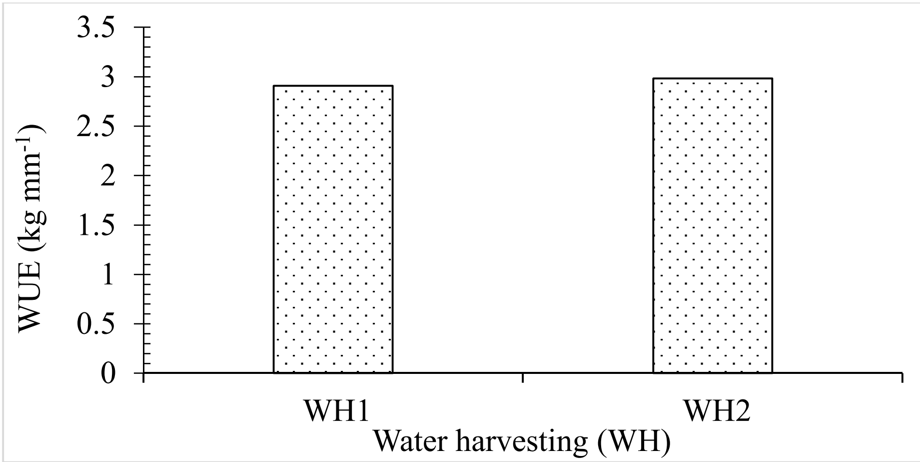


Figure 4.11: Effect of water harvesting (WH) on water use efficiency (WUE).
Key: WH1 = Flat beds; WH2 = Tie ridges.

4.15 Effect of crop rotation (CR) on nitrogen use efficiency (NUE) of wheat

The results depicting the effect of crop rotation (CR) on NUE are presented in Table 4.6. Nitrogen use efficiency (NUE) was significntly ($p < 0.001$) affected by crop rotation (CR). When wheat was planted before potato, the NUE values were significantly lower than any of the other pre-crops. However, when green pea and dolichos were planted before wheat, the NUE values increased considerably ($p < 0.001$) compared to potato and wheat as pre-crops. As wheat was followed with dolichos lablab and green pea, the value of NUE rose by 39% and 44%, respectively, when compared to potato. In comparison to potato as a pre-crop, NUE value increased by 54.17% under continuous wheat.

4.16 Effect of crop rotation (CR) on nitrogen utilization efficiency (NU_tE)

The results demonstrating the effect of crop rotation (CR) on nitrogen utilization efficiency are presented in Table 4.6. The cumulative effect of crop rotation reduced nitrogen utilization efficiency (NU_tE) considerably ($p < 0.001$), with lower values seen when wheat was preceded by potato than in any of the pre-crops. In terms of NU_tE, however, dolichos lablab and green peas were not substantially different. The three crops (dolichos lablab, green pea, and wheat) produced substantially more NU_tE than the pre-crops potato and wheat. When compared to potato as a pre-crop, the continuous wheat system (39.42 kg N kg N^{-1}) produced a considerably ($p < 0.001$) greater NU_tE value (29.12 kg N kg N^{-1}). When compared to continuous wheat, this resulted in a 35% drop in NU_tE. Overall, the contribution of legumes as a precursor crop to NU_tE was substantially greater than that of wheat and potato as pre-crops.

4.17 Effect of crop rotation (CR) on nitrogen uptake efficiency (NUpE)

The crop rotation treatments showed significant ($p < 0.001$) variations in N uptake efficiency (NU_pE) (Table 4.6). The NU_pE value obtained from green pea as a pre-crop was significantly greater ($p < 0.05$) than that obtained from dolichos and wheat as pre-crops. When wheat was preceded by green pea, the maximum NU_pE value (78.75 kg N ha^{-1}) was achieved, whereas the lowest value (54.84 kg N ha^{-1}) was obtained with potato as a pre-crop containing continuous wheat. Greenpea as a precursor crop raised NU_pE value by 44%, while dolichos increased NU_pE value by 31% when compared to potato as a pre-crop. As a pre-crop, continuous wheat (68.01 kg N ha^{-1}) had a substantially higher NU_pE value than potato (54.84 kg N ha^{-1}). This resulted in a 19% increase in NU_pE value due to wheat as a pre-crop compared to potato.

Table 4.6: Effect of crop rotation on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NU_tE), and nitrogen uptake efficiency (NU_pE) of wheat

Pre-crop in the rotation	Crop Rotation Cycle	NUE (%)	NU_tE (kg kg N^{-1})	NU_pE (kg kg N^{-1})
Dolichos	W – Dol – W	61.19 a	37.73 a	71.81 b
Green pea	W – Gp – W	63.15 a	37.98 a	78.75 a
Potato	W – Pot - W	43.91 c	29.12 b	54.84 c
Wheat	W – W - W	54.17 b	39.42 a	68.01 b
LSD (0.05)	-	5.23	2.264	6.57
CV (%)	-	4.7	3.1	4.8

Key: Means followed by the same letter(s) in the same column are not significantly different at $p < 0.05$; W= wheat; Dol = dolichos; Gp = green pea;

4.18 Effect of pre-crop on water use efficiency (WUE) of wheat

Table 4.7 shows the impact of pre-crop (Crop rotation) on water usage efficiency (WUE). When wheat was cultivated according to dolichos lablab, the greatest WUE value (3.438 kg mm^{-1} ha^{-1}) was attained. In comparison to when wheat was followed by potato, this equates to a 35 percent rise in WUE. Green pea as a pre-crop also enhanced wheat WUE by 27% as compared to potato as a pre-crop. Green pea and wheat as pre-crops, on the other hand, had no significant variations in WUE value. When the effect of the two legumes (dolichos lablab and green pea) as pre-crops was compared, dolichos lablab (3.438 kg mm^{-1} ha^{-1}) had a significantly higher WUE value than greenpea (3.085 kg mm^{-1} ha^{-1}). As a result, compared to green pea, potato, and continuous wheat in a short crop rotation system, dolichos lablab is a comparatively superior pre-crop for increasing wheat WUE.

Table 4.7: Effect of crop rotation (CR) on water use efficiency (WUE) of wheat

Pre-crop before wheat crop	**Crop Rotation Cycle**	**WUE (Kg mm^{-1} ha^{-1})**
CR1=Dolichos	W – Dol – W	3.438a
CR2=Green pea	W – Gp – W	3.085b
CR3=Potato	W – Pot – W	2.25c
CR4=Wheat	W – W – W	3.003b
LSD ($p < 0.05$)	**-**	**0.273**
CV (%)	**-**	**3.8**

Means followed by the same letter(s) in the same column are not significantly different at $p \le 0.05$. Key: W = wheat; Dol = dolichos; Gp = green pea; pot = potato.

4.19 Interaction effects of crop rotation, water harvesting (WH) and soil fertility management (SFM) on water use efficiency (WUE) of wheat

Figure 4.12 shows the findings illustrating the three-way interaction effects of CR, WH, and SFM on wheat WUE. The interactions of CR, WH, and SFM on the WUE value of the succeeding wheat crop indicated significant ($p < 0.001$) variations on the WUE value. In comparison to under tie ridged plots, Dolichos lablab as a pre-crop in conjunction with flatbeds and FYM at 5 tonnes ha^{-1} resulted in a considerably higher WUE value. Similarly, with green pea as a preceding crop fertilized with FYM on flat bed, the WUE value was greater than the other SFM methods tested. Green manure showed a comparably better WUE value in both cases, using dolichos lablab and green pea as pre-crops. While the use of higher rates of inorganic N sources at 50 and 75 kg N ha^{-1} resulted in better WUE values for potato as a pre-crop on either flat or tie ridged plots. Organic sources of N had a much higher effect beneath flat beds as well as tie ridged plots in continuous wheat (CR4). The maximum WUE value was seen in flatbeds when the SFM strategy was administered as green manure at 2.5 tonnes ha^{-1}, whereas the highest WUE value was observed in tie ridged plots when FYM was used as the SFM strategy.

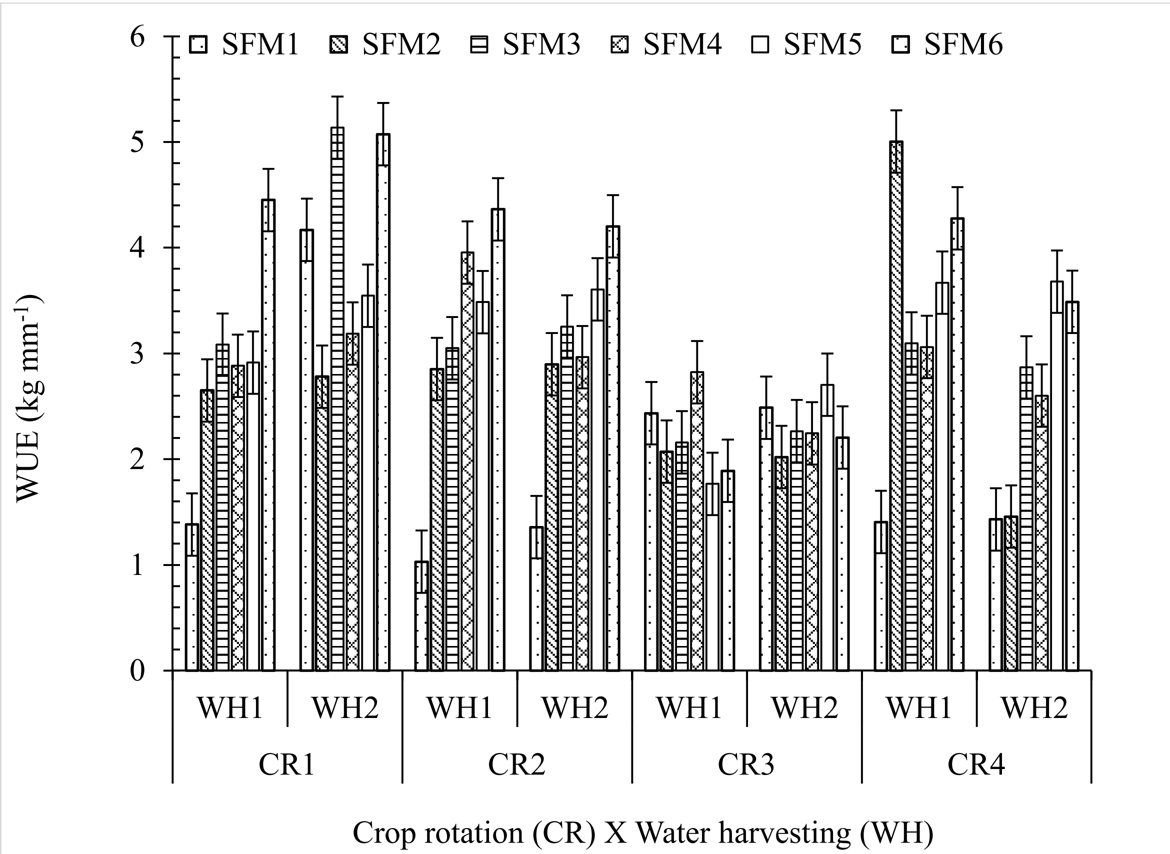


Figure 4.12: Interaction effects of crop rotation (CR), water harvesting (WH) and soil fertility management (SFM) on water use efficiency (WUE) of wheat.

Key: SFM1 = Untreated control; SFM2: Farm Yard Manure (FYM) at 5 tonnes ha^{-1}; SFM3 = Green manure (*L. purpureus*) at 2.5 tonnes ha^{-1}; SFM4 = 25 kg N ha^{-1}; SFM5 = 50 kg N ha^{-1}; SFM6 = 75 kg N ha^{-1}.

4.20 Effect of soil fertility management (SFM) on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NUtE) and nitrogen uptake efficiency (NUpE)

Table 4.8 displays the impact of soil fertility management (SFM) techniques on NUE, nitrogen utilization efficiency (NU_tE), and nitrogen uptake efficiency (NU_pE). The results indicated that SFM had a significant ($p < 0.001$) effect on NUE. Organic sources (FYM and green manure = *L. trichandra*) as well as the lowest amount of inorganic fertilizer (25 kg N ha^{-1}) resulted in considerably higher NUE values than the untreated control, inorganic fertilizer at 50 kg N (recommended rate), and 75 kg N ha^{-1} in the SFM treatments (50% higher than recommended rate). Farm yard manure (FYM) at 5 tonnes ha^{-1} raised NUE by 42%, whereas Green manure (*L. trichandra* at 2.5 tonnes ha^{-1}) enhanced NUE by 35%, and the application of the least amount of inorganic fertilizer (25 kg N ha^{-1}) increased NUE by 41%. As a result, it was clear that organic-based fertilizer sources and the lowest rate of inorganic fertilizer had a higher impact on wheat NUE than the other SFM methods (N at 50 and 75 kg N ha^{-1}). Higher rates of inorganic nitrogen sources resulted in lower NUE values.

In the case of NU_tE, no significant variations were found across the SFM methods. While all of the SFM techniques studied had a significant ($p < 0.05$) effect on NU_pE. However, in the case when inorganic fertilizer was administered at 25 kg N ha^{-1}, FYM at a ate of 5 t ha^{-1} resulted in asignificantly higher NU_pE value (80 kg N ha^{-1}) than the untreated control (63.12 kg N ha^{-1}) and the remainder of SFM methods (which is 50 percent lower than the recommended rate). The reduced rate of N application (25 kg N ha^{-1}) resulted in a NU_pE value that was not significantly different from that achieved with 2.5 t ha^{-1} of green manure (*L. trichandra*). With the application of green manure (*L. triachandra*) at 2.5 tonnes ha^{-1}, the influence of the lowest rate of N (25 kg ha^{-1}) on the efficiency of N recovery (NU_pE) was similarly not significant.

Table 4.8: Effect of soil fertility management (SFM) on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NU_tE) and nitrogen uptake efficiency (NU_pE) of wheat

Soil Fertility Management (SFM) strategies	NUE (%)	NU_tE (kg N ha^{-1})	NU_pE (kg kg N ha^{-1})
SFM1 = Untreated control	43.82 c	35.93	63.12 cd
SFM2 = Farm Yard Manure (FYM) 5 t ha^{-1})	62.43 a	35.49	80 .00a
SFM3 = Green Manure (*L. trichandra* 2.5 t ha^{-1})	59.27 ab	35.78	70.86 bc
SFM4 = Inorganic Fertilizer 50% lower (25 Kg N ha^{-1})	61.61 a	36.39	74.15 ab
SFM5 = Inorganic Fertilizer (50 kg N ha^{-1})	52.88 b	37.28	60.96 d
SFM6 = Inorganic Fertilizer 50% higher (75 kg N ha^{-1})	53.63 b	35.49	61.01 d
LSD (0.05)	6.94	**NS**	8.8
CV (%)	21.7	**12.2**	22.4

Means followed by the same letter(s) in the same column are not significantly different at $p < 0.05$; Key: SFM = Soil Fertility Management.

4.21 Interaction effect of crop rotation (CR) and soil fertility management (SFM) on nitrogen use efficiency (NUE) of wheat

Figure 4.13 depicts the effects of crop rotation (CR) and soil fertility management (SFM) on NUE. These findings have a statistically significant ($p < 0.05$) effect on NUE. When wheat was grown with green manure in plots that had previously been under green pea dolichos lablab and wheat, however, there were no significant variations in the value of NUE. However, when wheat was grown with green manure as a source of fertility on plots that had previously been under potato, the value of NUE was significantly lower than when green pea, dolichos lablab, and wheat were the precursor crops, resulting in a 46 percent increase in the value of NUE when wheat was fertilized with green manure at 2.5 t ha^{-1} and preceded by green pea compared to potato.

In plots where dolichos lablab, wheat, and potato were the pre-crops, inorganic sources of fertility in combination with different crops showed significant differences. For example, wheat planted with the lowest rate of N (25 kg N ha^{-1}) in plots preceded by green pea yielded a higher value of NUE than plots where dolichos lablab, wheat, and potato were the pre-crops yielded a higher value of NUE than plots where dolich NUE was substantially lower when wheat was planted with 50 kg N ha^{-1} and 75 kg N ha^{-1} after green pea, dolichols labalab, wheat, and potato than when wheat was cultivated with the lowest rate of N (25 kg N ha^{-1}) before the same crops. With increasing rates of inorganic fertilizer, the impact of green pea as a precursor crop on NUE was reduced by 31% and 36%, respectively, compared to inorganic fertilizer at 50 kg and 75 kg N ha^{-1}.

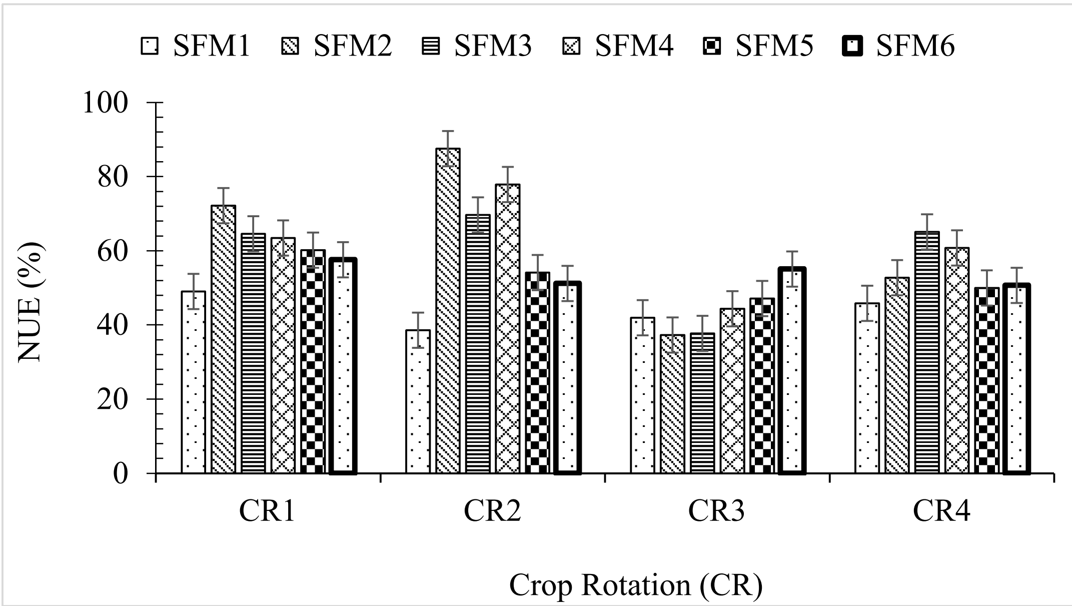


Figure 4.13: Interaction effect of crop rotation (Pre-crop) and soil fertility management (SFM) on nitrogen use efficiency (NUE) of wheat

Key: SFM1 = untreated control; SFM2 = Farm yard manure (FYM) at 5 tonnes/ha; SFM3 = green manure (*L. trichandra*); SFM4 = inorganic N source at 25 kg N/ha; SFM5 = inorganic source at 50 kg N/ha; SFM6 = inorganic source at 75 kg N/ha.

4.22 Interaction effect of crop rotation (CR) and soil fertility management (SFM) on nitrogen utilization efficiency (NUtE) of wheat

Figure 4.14 depicts the influence of crop rotation (CR) and soil fertility management (SFM) on nitrogen use efficiency (NU_tE). Crop rotation (CR) and soil fertility management (SFM) had a significant interaction impact on wheat NU_tE. Nitrogen use efficiency (NU_tE) was substantially impacted ($p < 0.05$) by the interaction between soil fertility management (SFM) methods and dolichos lablab, green pea, and wheat as pre-crops. Only 75kg N ha^{-i} inorganic fertilizer caused a significant difference in NUtE in wheat plots after potato. In comparison to dolichos lablab and green pea as pre-crops, wheat planted in untreated control (SFM1) plots after potato as a pre-crop considerably lowered the NUtE value (by 26 and 32 percent, respectively). Wheat treated with inorganic fertilizer (SFM5) at 50 kg N ha^{-1} in plots previously inhabited by dolichos lablab and green pea, on the other hand, raised NU_tE value by 14 and 12%, respectively, in plots previously occupied by dolichos lablab and green pea. It was clear that planting wheat in plots previously inhabited by legumes (dolichos lablab and green pea) with the prescribed rate of inorganic fertilizer (50 kg N ha^{-1}) enhanced the use efficiency of the recovered N. (uptake). After potato, wheat treated with the greatest rate of inorganic fertilizer (75 kg N ha^{-1}) had a higher NU_tE value than wheat fertilized with a lower rate of inorganic N fertilizer and organic fertilizer. Wheat's capacity to use either the inherent or applied N was clearly increased when modest rates of inorganic fertilizers were used with legumes as pre-crops. Because legumes can repair atmospheric N2 symbiotically, they only need a little amount of nitrogen fertilizer. As a result, using legumes as pre-crops and applying more than 50 kg N ha^{-1} decreased wheat's capacity to use applied or inherent soil N. (reduced NU_tE). This might be explained by the fact that increased N levels reduced the ability of soil microbes to fix nitrogen.

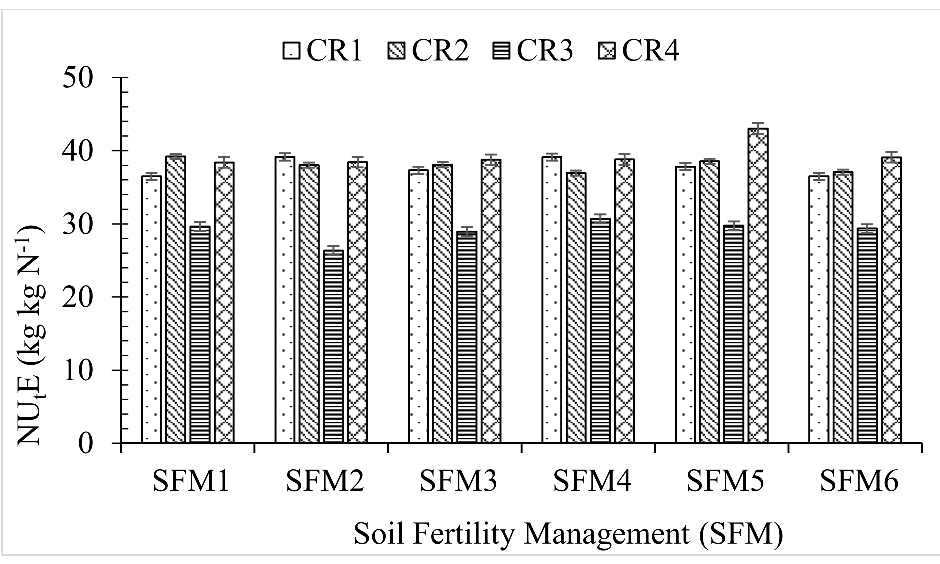


Figure 4.14: Interaction effect of crop rotation (Pre-crop) and soil fertility management (SFM) on nitrogen utilization efficiency (NU_tE) of wheat

Key: CR1 = Wheat – dolichos – wheat; CR2 = wheat – Green pea – wheat; CR3 = wheat – potato – wheat; CR4 = wheat – wheat – wheat; Key: SFM1 = untreated control; SFM2 = Farm yard manure (FYM) at 5 tonnes/ha; SFM3 = green manure (*L. trichandra*); SFM4 =

inorganic N source at 25 kg N/ha; SFM5 = inorganic source at 50 kg N/ha; SFM6 = inorganic source at 75 kg N/ha.

4.23 Interaction effect of crop rotation (Pre-crop) and soil fertility management (SFM) on nitrogen uptake efficiency (NU_pE) of wheat

Figure 4.15 shows the interaction impact of crop rotation (CR) and soil fertility management (SFM) on NU_pE. The combination between green manure and potato as a pre-crop had a significant ($p < 0.05$) impact on NU_pE. When wheat was planted with 2.5 tonnes ha^{-1} of green manure and followed by green manure, the value of NUpE increased by 43 percent compared to when wheat was treated with green manure and followed by potato.

In the area of inorganic sources of fertility, wheat planted with the lowest rate of nitrogen (25 kg N ha^{-1}) in plots preceded by green pea had a higher NU_pE value than plots where dolichos lablab, wheat, and potato were the pre-crops. NU_pE levels were substantially lower when wheat was planted with 50 kg N ha^{-1} and 75 kg N ha^{-1} after green pea, dolichos lablab, wheat, and potato than when wheat was cultivated with the lowest rate of N (25 kg N ha^{-1}) before the same crops. When comparing inorganic fertilizer rates of 25 kg N ha^{-1} and green pea to inorganic fertilizer rates of 50 and 75 kg N ha^{-1} with wheat as a pre-crop, the mean value of NU_pE was higher by 36% and 41%, respectively. Because of the interaction between the usage of green manure and various pre-crop systems, there were no significant variations in the value of NU_pE.

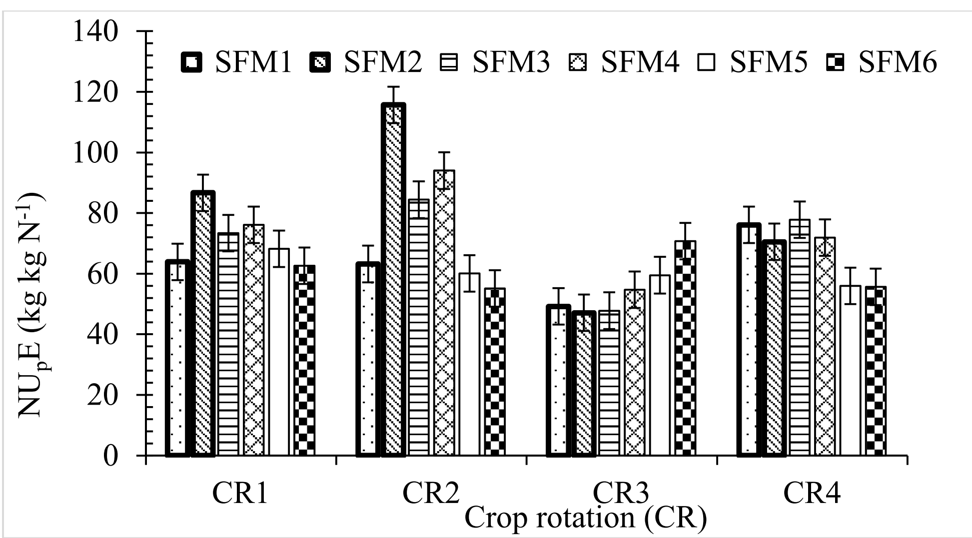


Figure 4.15: Interaction effect of crop rotation (Pre-crop) and soil fertility management (SFM) on nitrogen uptake efficiency (NU_pE) of wheat

Key: SFM1 = untreated control; SFM2 = Farm yard manure (FYM) at 5 tonnes/ha; SFM3 = green manure (*L. trichandra*); SFM4 = inorganic N source at 25 kg N/ha; SFM5 = inorganic source at 50 kg N/ha; SFM6 = inorganic source at 75 kg N/ha. CR1 = Wheat – Dolichos – Wheat; CR = Wheat – Green pea – Wheat; CR3 = Wheat – Potato – Wheat and CR4 = Wheat – Wheat – Wheat

4.24 Effect of soil fertility management (SFM) on water use efficiency (WUE) of wheat

The findings of the influence of soil fertility management (SFM) on water usage efficiency (WUE) are presented in Table 4.9. These findings indicated that SFM has a significant ($p < 0.05$) effect on wheat WUE, regardless of whether the source is inorganic or organic. Inorganic sources of SFM tactics, on the other hand, have a higher effect than organic sources. Using inorganic fertilizer at 75 kg N ha^{-1}, the greatest WUE (3.743 kg mm^{-1} ha^{-1}) was attained (SFM6). Inorganic fertilizer at 50 kg ha^{-1} (recommended rate) and green manure at 2.5 tonnes ha^{-1} (supplying roughly 24.75 kg N ha^{-1} equivalent) were then applied, yielding WUE values of 3.171 and 3.114 kg mm^{-1} ha^{-1}, respectively. The rise in WUE value owing to the maximum rate of inorganic fertilizer (75 kg ha^{-1}) was around 91 percent more than the untreated control, while the increases were 38 percent and 20 percent higher, respectively, when compared to FYM at 5 tonnes ha^{-1} and green manure at 2.5 tonnes ha^{-1}. This demonstrates the need of applying soil amendments to the land. The highest rate of inorganic fertilizer (75 kg N ha^{-1}) had the largest impact since an application of N at 75 kg ha^{-1} may have accelerated the establishment of wheat early enough to fill the plots. Early covering may have reduced open field evaporation while improving evapo-transpiration efficiency, resulting in higher WUE owing to inorganic sources rather than organic sources in SFM methods. Using inorganic fertilizer at 75 kg N ha^{-1}, the greatest WUE (3.743 kg mm^{-1} ha^{-1}) was attained (SFM6). Inorganic fertilizer at 50 kg ha^{-1} (recommended rate) and green manure at 2.5 t ha^{-1} (supplying roughly 24.75 kg N ha^{-1} equivalent) were then applied, yielding WUE values of 3.171 and 3.114 kg mm^{-1} ha^{-1}, respectively. The rise in WUE value owing to the maximum rate of inorganic fertilizer (75 kg ha^{-1}) was around 91 percent more than the untreated control, while the increases were 38 percent and 20 percent higher, respectively, when compared to FYM at 5 tonnes ha^{-1} and green manure at 2.5 tonnes ha^{-1}. This demonstrates the need of applying soil amendments to the land. The highest rate of inorganic fertilizer (75 kg N ha^{-1}) had the largest impact because an application of

N at 75 kg ha^{-1} might have accelerated the establishment of *T. aestivum* early enough to cover the plots. Early covering may have lowered open-field evaporation while improving evapo-transpiration efficiency, resulting in higher WUE.

Table 4.9: Effect of soil fertility management (SFM) on water use efficiency (WUE) of wheat

Soil Fertility Management (SFM)	Applied N ha^{-1}	WUE (Kg mm^{-1} ha^{-1})
SFM1 = Untreated control	No fertilizer	1.962d
SFM2 = Farm Yard Manure (FYM) 5 t ha^{-1}	50 kg ha^{-1}	2.717c
SFM3 = Green Manure (*L. trichandra* 2.5 t ha^{-1}	24.75 kg N ha^{-1}	3.114b
SFM4 = Inorganic Fertilizer 50% lower (25 Kg N ha-^{1})	25 kg N ha^{-1}	2.965bc
SFM5 = Inorganic Fertilizer (50 kg N/ha)	50 kg N ha^{-1}	3.171b
SFM6 = Inorganic Fertilizer 50% higher (75 kg N/ha)	75 N ha^{-1}	3.743a
LSD (0.05)	-	0.282
CV (%)	-	16.7

Means followed by the same letter(s) in the same column are not significantly different at $p < 0.05$.

4.25 Mean squares showing the effect of crop rotation (CR), water harvesting (WH), soil fertility management (SFM) and their interactions on yield and biomass of wheat

Table 4.10 shows mean squares demonstrating the influence of CR, WH, and SFM on yield and biomass. The effects of water harvesting (WH) on biomass ($p < 0.001$) and yield ($p < 0.001$) were significant. Crop rotation (CR) and SFM, on the other hand, had a substantial ($p < 0.01$) effect on yield but had no effect on biomass. On yield, there were significant two-way interaction effects involving WH x CR, CR x SFM, and WH x SFM. While there was a significant ($p < 0.01$) influence of the three-way interaction owing to CR x WH x SFM on yield, there was also a significant ($p < 0.01$) effect of the three-way interaction due to CR x WH x SFM on yield.

Table 4.10: Mean squares showing the effect of factors and their interactions on grain yield and biomass

Source of variation	d.f	Grain Yield	Biomass
Rep stratum	2	170559	1011567
Water Harvesting (WH)	1	68885	278282147***
Residual	6	96637	2486833
Crop Rotation (CR)	3	4043216**	3023230
WH x CR	3	1405269**	327497
Residual	8	83443	884697
Soil Fertility Management (SFM)	5	2084977**	1455007
CR x SFM	15	414976**	1138137
WH x SFM	5	516217**	564371
CR x WH x SFM	15	191432**	1583192
Residual	80	48198	922779
Total	**143**		

Key: ** - $p < 0.01$; *** - $p < 0.001$

4.26 Effect of pre-crops in the short crop rotation (CR) on yield

As shown in Table 4.11, the cumulative effect of crop rotation (CR) had a signifcant ($p < 0.05$) effect on wheat yield. When wheat was preceded by dolichos lablab and green pea in the short crop rotation (CR) cycle, yield was significantly greater ($p < 0.05$) than when wheat was preceded by potato and wheat. When Dolichos lablab and green pea were used as pre-crops, wheat yields were significatly greater than when potato was used as the predecessor crop. Dolichos lablab and green pea as pre-crops improved wheat production by 92 percent and 73 percent, respectively, as compared to potato. As a result, using potato as a pre-crop for wheat resulted in a reduced yield. Because legumes provide a substantial contribution to cereal output as a preceding crop, they should be included in short crop rotation systems to increase wheat yield at a cheap cost. In contrast to to non-leguminous crops, it was clear that wheat cultivated after potato produced considerably lower yields than wheat grown directly following wheat.

4.27 Effect of pre-crops in the short crop rotation (CR) on biomass

Crop rotation (CR) had a significant ($p < 0.05$) effect on wheat biomass, as shown in Table 4.11. When wheat was planted before dolichos lablab, green pea, or even continuous wheat in the short crop rotation (CR) cycle, yields were higher than when wheat was planted before potato. When Dolichos lablab and green pea were used as pre-crops, the biomass produced was considerably greater than when potato was used as the predecessor crop. In comparison to potato as a pre-crop, the increase in biomass value after either dolichos lablab or green pea was around 93 percent. As a result, using potato as a pre-crop for wheat resulted in reduced biomass. When compared to non-leguminous crops, it was clear that wheat cultivated after potatoes produced considerably less biomass than wheat planted directly after legumes or continuous wheat.

Table 4.11: Effect of pre-crops in the short crop rotation (CR) on yield and biomass

Pre-crop effect in the rotation	Crop Rotation (CR)	Yield ($Kg\ ha^{-1}$)	Biomass ($kg\ ha^{-1}$)
CR1=Dolichos	W – Dol – W	1603 a	6035 a
CR2=Green pea	W – Gp – W	1439 ab	6283 a
CR3=Potato	W – Pot –W	834 c	426 b
CR4=Wheat	W – W – W	1400 b	5536 a
LSD (0.05)	-	179.3	909.5
Cv (%)	-	6.8	10

Means followed by the same letter(s) in the same column are not significantly different at $p < 0.05$; CR = Crop Rotation; W = Wheat; Dol = Dolichos; Gp = Green pea; Pot = Potato

4.28 Effect of soil fertility management (SFM) on grain yield of wheat

Table 4.12 shows the data indicating the influence of soil fertility management (SFM) on wheat yield. Wheat yield was impacted by soil fertility management (SFM) in a significant ($p < 0.05$) way. The grain yield of wheat planted without fertilizer (untreated control) was lower than that of all the treated plots. With the application of inorganic fertilizer (75 kg N ha^{-1}, 50 percent greater than the required rate of 50 kg N ha^{-1}), the maximum grain yield (1710 kg ha^{-1}) was attained. This increase in yield (due to 75 kg N ha^{-1}) was 28% greater than the lowest rate of N

(25 kg N ha^{-1}) and 52% higher than the untreated control. Compared to FYM at 5 tonnes ha^{-1} and green manure (*L. trichandra*) at 2.5 tonnes ha^{-1}, the maximum rate of N (75 kg N ha^{-1}) improved yield by 38 percent and 22 percent, respectively, as compared to organic fertilizers. When compared to organic sources, the application of inorganic fertilizer at the maximum rate (75 kg N ha^{-1}) resulted in the best wheat production.

4.29 Effect of soil fertility management (SFM) on biomass of wheat

The results showing the the influence of soil fertility management (SFM) on wheat yield are presented in Table 4.12. Wheat yield was impacted by soil fertility management (SFM) in a significant ($p < 0.05$) way. The grain yield of wheat planted without fertilizer (untreated control) was lower than that of all the treated plots. With the application of inorganic fertilizer (75 kg N ha^{-1}, 50 percent higher than the recommended rate of 50 kg N ha^{-1}), the highest grain yield (1710 kg ha^{-1}) was achieved. This increase in yield (due to 75 kg N ha^{-1}) was 28% greater than the lowest rate of N (25 kg N ha^{-1}) and 52% higher than the untreated control. Compared to FYM at 5 tonnes ha^{-1} and green manure (*L. trichandra*) at 2.5 tonnes ha^{-1}, the maximum rate of N (75 kg N ha^{-1}) improved yield by 38 percent and 22 percent, respectively, as compared to organic fertilizers. When compared to organic sources, the application of inorganic fertilizer at the maximum rate (75 kg N ha^{-1}) resulted in the best wheat production.

Table 4.12: Effect of soil fertility management (SFM) on yield and biomass of wheat

Soil Fertility Management (SFM)	**Rate of N ha^{-1}**	**Yield (kg ha^{-1})**	**Biomass (kg ha^{-1})**
SFM1 = Untreated control	No fertilizer	813 d	5864
SFM2 = Farm Yard Manure (FYM) 5 t/ha	50 kg ha^{-1}	1234 c	5802
SFM3 = Green Manure (*L. trichandra* 2.5 t/ha	24.75 kg N ha^{-1}	1400 b	6611
SFM4 = Inorganic Fertilizer 50% lower (25 Kg N/ha)	25 kg N ha^{-1}	1334 bc	5881
SFM5 = Inorganic Fertilizer (50 kg N/ha)	50 kg N ha^{-1}	1423 b	5730
SFM6 = Inorganic Fertilizer 50% higher (75 kg N/ha)	75 N ha^{-1}	1710 a	5818
LSD (0.05)	-	126.1	**NS**
Cv (%)	-	16.6	**18.6**

Means followed by the same letter(s) in the same column are not significantly different at $p < 0.05$; ns = Not significant

4.30 Interaction effects of crop rotation (Pre-crop), water harvesting (WH) and soil fertility management (SFM) on grain yield of wheat

Figure 4.16 displays the findings of the three-way interaction effects of CR, WH, and SFM on wheat grain yield. The interactions of CR, WH, and SFM on the grain yield of the following wheat crop indicated signiificant ($p < 0.001$) variations in grain yield. In comparison to other SFM methods, *L. purpereus* as a pre-crop on flat beds fertilized with the maximum rate of inorganic N (75 kg N ha^{-1}) resulted in a significantly ($p < 0.001$) higher grain production. On tie ridged plots, a different pattern in grain yield was found, with green manure at 2.5 tonnes ha^{-1} producing the highest grain yield and the highest rate of inorganic N (75 kg ha^{-1}) producing the second best grain yield. Regardless of the water collecting technique, green pea as a pre-crop treated with the greatest rate of inorganic N (75 kg N ha^{-1}) yielded the maximum grain production (either flat beds or tie ridged plots). Potato as a pre-crop produced much lower grain production than all other pre-crops tested. Potato was grown as a pre-crop on flat beds with the lowest nitrogen rate (25 kg N ha^{-1}) and yielded substantially more grain. There were no significant changes in grain output owing to green manure, the lowest rate of inorganic N (25 kg N ha^{-1}) or the maximum rate of inorganic N (50 kg N ha^{-1}) under the tie ridges (75 kg N ha^{-1}). The maximum grain yield was achieved using wheat as a pre-crop fertilized with FYM at a rate of 5 tonnes ha^{-1} on a flatbed. Under tie ridges, however, and with the second greatest rate of inorganic N (50 kg N ha^{-1}).

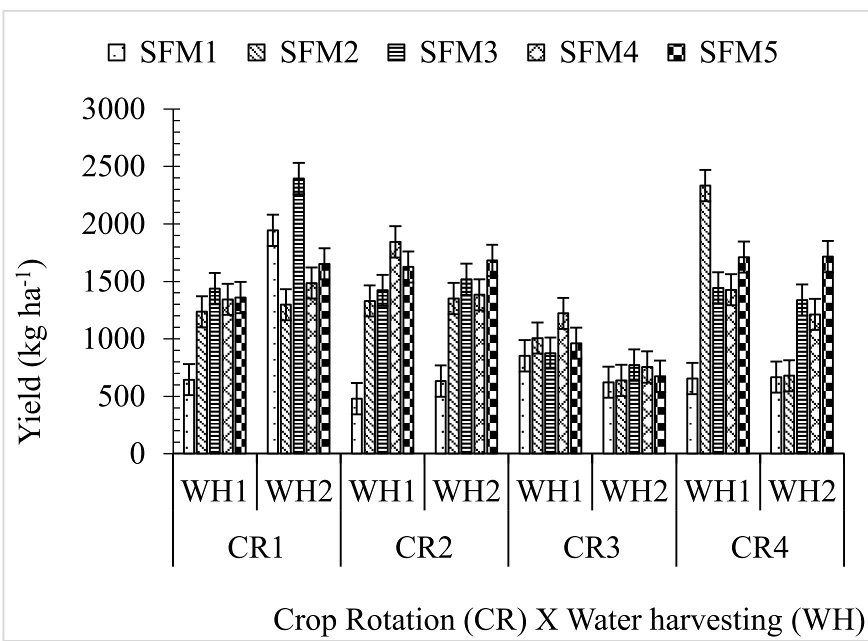


Figure 4.16: Interaction effects of crop rotation (Pre-crop), water harvesting (WH) and soil fertility management on grain yield of wheat

Key: SFM1 = Untreated control; SFM2: Farm Yard Manure (FYM) at 5 tonnes ha^{-1}; SFM3 = Green manure (L. purpureus) at 2.5 tonnes ha^{-1}; SFM4 = 25 kg N ha^{-1}; SFM5 = 50 kg N ha^{-1}; SFM6 = 75 kg N ha^{-1}; CR1 = Wheat – Dolichos – Wheat; CR2 = Wheat – Green pea – Wheat; CR3 = Wheat – Potato – Wheat; Wheat – Wheat - Wheat

4.31 Correlation coefficients depicting relationships between selected soil and water parameters

Except for mean soil temperature, which was shown in Table 4.13, water usage efficiency (WUE) was not significantly associated to soil organic carbon (SOC), soil nitrogen (N), or soil moisture. Water usage efficiency (WUE) and soil temperature (ST) have a somewhat favorable association ($r = 0.320$; $p < 0.0001$). However, a weak negative ($r = -0.193$; $p < 0.05$) correlation between soil N and SOC was discovered. The moderately positive relationship between WUE and ST could be explained by the fact that plants increase transpiration efficiency when temperatures are relatively warm, improving WUE. The lack of a strong connection between N and SOC may be owing to the fact that soil microorganisms use most of the soil N to breakdown crop waste, causing SOC to rise while N decreases until after mobilization.

Table 4.13: Correlation coefficients depicting the relationships between selected soil and water related parameters

	WUE	SOC	Soil N	Soil moisture	Mean Soil Temp
WUE	1.00				
SOC	-0.013	1.00			
Soil N	0.086	-0.193*	1.00		
Soil moisture	0.155	0.010	-0.027	1.00	
Mean Soil Temp	0.320***	-0.161	0.020	0.215*	1.00

***- Correlation is significant at $p < 0.001$ level; **- Correlation is significant at $p < 0.01$ level; *- Correlation is significant at $p < 0.05$ level; ns = not significant; WUE water use efficiency; SOC = soil organic carbon;

4.32 Correlation coefficient depicting the relationship between yield and NUE plus its associated attributes

Table 4.14 shows correlation coefficients that illustrate relationships between yield and NUE, as well as its related characteristics. Biomass ($r = 0.483$; $p < 0.0001$), NU_tE ($r = 0.297$; $p < 0.0001$), and NUE ($r = 0.442$; $p < 0.0001$) were all positively associated with yield. Other associations were found between biomass and NUtE ($r = 0.693$; $p < 0.0001$), biomass and NUE ($r = 0.412$; $p < 0.0001$), and biomass and NU_pE ($r = 0.380$; $p < 0.0001$), as well as biomass and NUpE ($r = 0.380$; $p < 0.0001$). NUE and NUpE had a substantial positive association ($r = 0.911$; $p < 0.0001$) as well. In conclusion, high NUE enhanced yields, therefore crop management methods that help to improve NUE as well as wheat yields. The close link between NUE and NU_pE also provides an opportunity to improve wheat NUE by addressing strategies to improve applied or inherent N uptake in the soil.

Table 4.14: Correlation coefficients depicting the relationship between yield and NUE plus its associated attributes

	Yield	**Biomass**	**NU_tE**	**NUE**	**NU_pE**
Yield	1.00				
Biomass	0.483***	1.00			
NU_tE	0.297***	0.693***	1.00		
NUE	0.442***	0.412***	0.133	1.00	
NU_pE	0.148	0.380***	0.134	0.911***	1.00

***- Correlation is significant at $p < 0.001$ level; **- Correlation is significant at $p < 0.01$ level; *- Correlation is significant at $p < 0.05$ level; NU_tE = N utilization efficiency; NUE = N use efficiency; NU_pE = N uptake efficiency.

4.33 Correlation coefficients depicting relationships between WUE and yield; and biomass

Table 4.15 shows the results in the form of correlation coefficients depicting the relationships between WUE and yield as well as biomass. Water use efficiency (WUE) exhibited a strong correlation with yield and biomass. The association between WUE and yield was significantly positive ($r = 0.944$; $p < 0.001$), whereas the relationship between WUE and biomass was moderately favorable (r = 0.342; $p < 0.001$). The findings in this part allow us to appreciate the relevance of WUE in influencing wheat yield more than biomass. WUE, on the other hand, is crucial in both instances since it has a direct impact on the photosynthetic process of plants. Because WUE is defined as the quantity of carbon (C) absorbed as grain or biomass generated per unit of water utilized by the crop, this is extremely significant.

Table 4.15: Correlation coefficients depicting the relationships between WUE, grain yield and biomass

	WUE	Yield	Biomass
WUE	1.00		
Yield	0.944***	1.00	
Biomass	0.342***	0.483***	1.00

***. Correlation is significant at the 0.001 level; **. Correlation is significant at the 0.01 level; *. Correlation is significant at the 0.05 level; WUE water use efficiency

4.34 Relationships between yield and selected soil and water parameters

Table 4.16 displays the correlation coefficients that illustrate the connections between yield and chosen soil related factors, as well as WUE. However, there was a mild positive connection between yield and soil moisture (r = 0.231; $p < 0.001$), whereas the link between yield and soil temperature was substantially favorable (r = 0.448; $p < 0.001$).

Table 4.16: Correlation coefficients depicting the relationships between selected soil and water parameters

	SOC	Soil N	Soil moisture	Mean Soil Temp (^{0}C)
SOC	1.00			
Soil N	-0.193*	1.00		
Soil moisture	0.010	-0.027	1.00	
Mean Soil Temp (^{0}C)	-0.161	0.020	0.215*	1.00

***Correlation is significant at $p < 0.001$ level; **Correlation is significant at $p < 0.01$ level; *Correlation is significant at $p < 0.05$ level; WUE water use efficiency; SOC = soil organic carbon

CHAPTER FIVE

DISCUSSION

5.1 Rainfall characteristics during long rains in seasons I (2014), II (2015) and III (2016)

The study area featured a bi-modal rainfall pattern, with season I (2014), which fell between August and November, having 42 percent less rainfall than season II (April–August 2015). Season III (2016), on the other hand, got more rainfall than seasons I and II, which were greater by 52 and 17%, respectively. Season I (2014), which lasted from August to November 2014, received 39% of the total rainfall, whereas seasons II (2015) and III (2016) received 64 and 66%, respectively, of the yearly rainfall.

Season III, on average, had more seasonal rainfall (692.5 mm) than seasons I and II (333.3 mm and 333.3 mm, respectively) (572.2 mm). Seasons I and III had better rainfall distribution than season II, which had nearly 66% of the growing season's rainfall fall in April and May. The yearly rainfall in the third season was roughly 15% greater than in seasons I and II. The amount of rain received in each of the three seasons, however, was sufficient for three crops cultivated throughout the research period.

KALRO Njoro receives around 960 mm of rainfall every year, according to Jaetzold & Schmidt (2011). The quantity of rain received during the research period was somewhat less in the first (2014) and second (2015) years, when yearly rainfall decreased by 12 percent and 6.9 percent, respectively. However, the yearly rainfall was roughly 9% greater in the last season (2016). The quantity of rainfall obtained throughout the study seasons (2014, 2015, and 2016) was generally at least 30% of the annual rainfall, indicating that it was more than enough for the crops assessed.

5.2 Effect of water harvesting (WH) on nitrogen use efficiency (NUE), nitrogen utilization efficiency (NU_tE) and nitrogen uptake efficiency (NU_pE) of wheat

In-situ water harvesting (WH) takes several forms, including tie ridges, and is used to extend the retention of soil moisture and improve crop nutrient uptake (Silunge *et al.,* 2018). Two water harvesting (WH) techniques (WH1 = flat bed and WH2 = tie ridges) were tested to see how they affected NUE, NU_tE, and NU_pE. The lack of substantial changes in NUE, NU_tE, and NU_pE of wheat contrasts with the findings of Masebo *et al.* (2018), who found that tie ridges had an impact on maize (Zea mays) in Ethiopia. In situ WH methods are widely used to enhance the quantity of water retained in the soil profile by capturing or holding rain water where it falls, and this helps to concentrate the water near the crops root zone (Yazar & Ali, 2016). “In most cases, the impact of in-situ WH methods is felt in situations where moisture is scarce”. This means that WH strategies were unnecessary during the experiment because soil moisture was sufficient for the crops.

5.3 Effect of Crop Rotation (CR) on Nitrogen Use Efficiency (NUE), Nitrogen utilization efficiency (NU_tE) and Nitrogen uptake efficiency (NU_pE)

In comparison to the other cropping systems, the NUE value was significantly greater when wheat was preceded by legumes (dolichos lablab and green pea), according to the findings of this study. “When compared to green pea as the preceding crop, dolichos lablab had a considerably larger beneficial impact on NUE as a pre-crop in the rotation”. This was due to the fact that the legumes in the crop rotation enhanced the soil's ability to store more N while also influencing soil moisture accumulation. Legumes as cover crops (pre-crops) have significantly increased soil organic matter (SOM), which can hold moisture like a sponge and improve microbial activities, thereby contributing to soil ecosystem sustainability, and this according to Espinoza *et al.* (2012), has a great potential of increasing available N supply for subsequent cereals. The benefits of including legumes in a cropping sequence can improve soil quality, porosity, and structure (McCallum *et al.,* 2004; Rochester *et al.,* 2001), as well as influence specific microorganism populations in the rhizosphere (Kirkegaard *et al.,* 2008; Osborne *et al.,* 2010) for the benefit of subsequent N non-fixing crops. These advantages translate to improved soil N availability, resulting in higher N absorption and a beneficial impact on NUE. Thus, utilizing legumes in rotation with wheat in the humid tropics for increased Soil-N delivery should be promoted, especially given the current weather unpredictability, because it is linked with numerous N-related and non-N advantages. “Although grain legumes grown in rotation with annual cereal crops are expected to contribute to the total pool of N in the soil and improve cereal yields, the legume's expected N benefits may be positive or negative depending on the legume species and its interaction with the environment” (Danga *et al.,* 2009). “The fact that different legume species and cultivars growing in the same site can differ considerably in dry matter production, N fixation and accumulation, and residue quality has underlined the significance of choosing the correct legume species for a given wheat farming system" (FAO, 2016).

As a consequence of the findings of this study, dolichos labalab or green pea may be used in legume – wheat rotations in Njoro (which lies within the agro-ecological zone (AEZ = LH3) with an average annual rainfall of 935 mm (Jaetzold *et al.,* 2011). Although the results of this investigation showed that both green pea and dolichos labalab enhanced wheat's NUE value, green pea as a pre-crop had a much higher NUE value than dolichos lablab and potato, as well as under continuous wheat. Green pea's exceptional performance can be attributed to a number of factors. According to Kirkegaard *et al.* (2008), a previous green pea crop benefited 91% of the wheat production due to reduced leaf disease and weed infestation, whereas only 9% was assessed to have originated directly from N. Furthermore, break crops have been credited with improving wheat N nutrition simply because they have a better root structure, which improves the ability to utilize existing soil N or added N more efficiently (Cook, 1990).

As a result, increased soil N availability and improved soil moisture availability may have contributed to higher NU_pE and NUE values. The findings support those of Giller (2001) and Vanlauwe *et al.* (2010), who reported that grain legumes fix atmospheric N gas (N_2), which adds to the N economy of fields while also benefiting the subsequent crops. The research also shows that legumes in wheat – legume rotation systems produce high-quality organic residues in situ with a high N concentration and a low C to N ratio, assisting in integrated soil fertility management (ISFM). As such, it was clear that CR in combination with specific SFM methods was necessary to increase the impact of crop rotation on NUE. The biomass of the green pea and FYM night have created a sufficient amount of soil organic matter (SOC), which had a favorable impact. As a result, it served to cushion soil moisture, allowing it to be accessible for extended periods of time while also adding to the soil N pool. This contradicts the findings of Rahimizadeh *et al.* (2010), who found that wheat planted after potato had higher NUE, NU_tE, and NU_pE.

Furthermore, when wheat was planted with the lowest rate (25 kg N ha^{-1}) of inorganic fertilizer following green pea as a pre-crop, greater NUE values were achieved than when the maximum rate (75 kg N ha^{-1}) of inorganic fertilizer was utilized. The modest dose of inorganic fertilizer after green pea as a pre-crop might be the scientific explanation for the observed rise in NUE of wheat based on the data. This scenario might have offered a chance for soil microorganisms to increase soil fertility by metabolizing the N from the applied fertilizer as well as the fixation from the previous green pea that was not absorbed by plants. These findings are consistent with those of Hirel *et al.* (2011), who reported higher NUE of wheat at lower levels of crop output when N fertilization was significantly lower, and Soledad *et al.* (2015), who also reported "high NUE and NU_pE in wheat-lupin (*Lupinus spp.*)-green pea cycles". Planting a legume pre-crop instead of fallow with legume crops improved soil fertility and decreased nitrate leaching, contributing to greater NUE, according to other studies (Miller *et al.,* 2015; Muramoto *et al.,* 2011; Varvel & Wilhelm, 2018).

Crop rotation (CR) had a significant effect on soil moisture, with legume pre-crops resulting in higher soil moisture than potato and continuous wheat. Because NUE is a product of the two components, high soil moisture may have aided N absorption and utilization efficiency, resulting in higher NUE (NU_tE and NU_pE). The scientific rationale for this is that the humus content generated by the absorbed biomass from legumes may have also aided in the maintenance of the soil physical structure, therefore improving soil moisture retention. This is in line with findings of Dejene & Lemlem (2012), who reported that incorporating organic inputs into the soil increases water absorption, reduces water loss, and improves soil moisture content. In view of this, knowing the processes involved with NUE, particularly in regard to its major components (N uptake and utilization efficiency), is one of the most significant elements in defining management methods aimed at enhancing NUE (Uribelarrea *et al.,* 2007). The capacity of a plant to translocate ingested N (N uptakes) into grain is measured by NU_tE (Delogu *et al.,* 1998). The response of NU_tE to the previous crop was comparable to the response of NU_pE. With the exception of the potato – wheat rotation system, the highest value for wheat NU_tE was obtained with the continuous wheat system, while differences were not significant among the other rotations. Wheat cultivated following green pea or dolichos lablab had a NU_tE of around 5% lower than continuous wheat. The change in wheat NU_tE across crop rotations might be attributable to a variety of causes, including wheat yield fluctuation between rotations. These findings corroborate the hypothesis that the enhanced wheat NU_tE observed was due to an increase in wheat yield. In this study, preceding crops had the greatest impact on wheat production and the highest NU_tE value in the potato-wheat rotation. This is consistent with Muurinen *et al.* (2007), who found that increasing grain yield increased NU_tE and that NU_tE and yield had a significant relationship.

Crop rotation, according to López-Bellido & López-Bellido (2001), has a significant impact on resource usage. Nitrogen utilization efficiency (NU_tE) and yield, as well as biomass, had a significant relationship, according to the findings. This finding suggests that the impact of NU_tE on the accumulation of above-ground biomass is significant, and that it may be utilized to indirectly boost NUE via the NHI.

The crop's ability to absorb N from the soil is measured by its NU_pE. Raun & Johnson (1999) suggest increased NU_pE as a technique for increasing NUE. It is adversely affected by circumstances that decrease soil N, resulting in lower accumulation. These losses can be decreased by using appropriate techniques or best management practices (BMPs) that increase N availability for plant use, improve plant N absorption, and synchronize fertilizer treatments to agronomic demands (Sharma *et al.*, 2018). As a result, while attempting to address the issues connected with N loss, the strategy would be to balance crop-nutrient requirements while limiting losses in order to preserve a sustainable environment and improve economic advantages to farmers. In order to improve sustainable N management, the study focused on the impact of crop rotation systems on NUE and its related components, such as NU_tE and NU_pE. Nutrient uptake (NU_pE) was greater after legumes than after potato or continuous wheat. Badaruddin & Meyer (1994) and López-Bellido & López-Bellido (2009) both found similar findings. Green pea as a pre-crop had a higher wheat NU_pE value than dolichos lablab among the legume pre-crops. According to several studies, N linked with legume nodules and roots can account for 30-60% of total N collected by legumes (Khan *et al.,* 2003; McNeill & Fillery, 2008). Other research studying a faba bean (*Vicia faba* L.) – wheat sequence indicated that wheat may collect more than double the amount of N from nodulated roots associated with faba bean than from shoot residues (Jensen *et al.,* 2010). This study shows that legume roots and nodules may be a valuable source of N for subsequent crops. These findings corroborated those of Rahimizadeh *et al.* (2010), who found that wheat produced following a legume crop had higher NUE, NU_tE, and NU_pE in a wheat – legume rotation research done in Iran to assess the contribution of the legume preceding crop on the succeeding wheat crop.

When wheat was grown after green pea and dolichos lablab, the average NU_pE of 78.75 kg N ha^{-1} (equivalent to 1.575 kg N uptake kg^{-1} N supply) and 71.81 kg N ha^{-1} (equivalent to 1.436 kg N uptake kg^{-1} N supply) were higher than the average 0.49 kg N uptake kg^{-1} N supply reported by López-Bellido & López-Bellido, respectively (2001). These findings might be explained by the fact that the study in question was performed in a Mediterranean climate, as opposed to ours, which was conducted in a tropical setting. As a result, the discrepancies might be explained by changes in soils, experiment duration, and legume species utilized. The lower NU_pE of wheat produced after potato-wheat rotation contradicts the findings of Rahimizadeh *et al.* (2010), who found a greater NU_pE value in wheat grown after potato-wheat rotation. "The decreased NU_pE recorded on wheat following potato might be due to the fact that potato, as a gross feeder, mines the majority of the soil N, as well as the fact that the harvested tubers take a significant quantity of nutrients out of the soil". The influence of this rotation in depleting soil N is demonstrated by the considerably greater value of NU_pE measured in continuous wheat (cereal monoculture).

The results of crop rotation and soil fertility interactions revealed that wheat NU_pE was influenced by previous crop and soil fertility management. Furthermore, for NU_pE, there was a strong interaction between the previous crop and FYM. The green pea - wheat and potato - wheat rotations had the greatest (78.75 kg N ha^{-1}) and lowest (54.84 kg N ha^{-1}) NU_pE of wheat, respectively. Wheat planted after green pea but fertilized with FYM at 5 t ha^{-1} had a 59% higher NU_pE than the green pea - potato system, but there was no significant difference in wheat NU_pE between the green pea - wheat and dolichos lablab - wheat cycles. Fluctuation in NU_pE, according to Moll *et al.* (1982), may be distinguished from grain yield variation since it has a direct effect in increasing NUE. According to Lopez-Bellido & Lopez-Bellido (2001), variations in grain yield, which is directly connected to crop NU_pE, account for variance in the NU_pE index. The positive contribution of FYM in enhancing the effect of green pea as a pre-crop on NU_pE of wheat could be attributed to the fact that the biological nitrogen fixing bacteria (BNF) in the green pea could have benefited from the application of FYM as a source of carbon. This agrees with findings of Danga *et al.* (2009), who reported enriched Soil N by various grain legumes through BNF which subsequently enhanced wheat yields and non-N benefits such as reduction of wheat root rot incidence which in turn enhanced added NU_pE. Espinoza *et al.* (2015) also reported that "wheat cultivated after lupine and greenpea was more efficient in NU_pE and NU_tE than cereal".

The beneficial impact of FYM in improving the effect of green pea as a pre-crop on wheat NU_pE might be ascribed to the fact that the green pea's BNF bacteria may have benefitted from the use of FYM as a carbon source. This is consistent with the findings of Danga *et al.*

(2009), who found that different grain legumes supplemented soil N through BNF, resulting in increased wheat yields and non-N advantages such as reduced wheat root rot incidence, which in turn increased additional N absorption. Wheat planted after lupine and greenpea was similarly more effective in N absorption and utilization than cereal, according to Espinoza *et al.* (2015).

5.4 Effect of soil fertility management (SFM) on Nitrogen use efficiency (NUE) and its associated components (NU_tE and NU_pE)

Plant seed yield in relation to the amount of N supplied determines NUE, which is typically made up of both NU_pE and NU_tE (Moll *et al.,* 1982). Total shoot N relative to the quantity of N given to the soil is described as NU_pE. The availability of soil N influences root N absorption, which is regulated by plant N assimilation mechanisms and N metabolite levels, as well as the plant's N requirement (Nacry *et al.,* 2013; Ruffel *et al.,* 2011; Stahl *et al.,* 2016).

In comparison to inorganic sources of fertility, in this study organic sources produced the highest competitive NUE value. Green manure (*L. trichandra* at 2.5 tonnes ha^{-1}) enhanced the NUE of wheat by 35%, whereas FYM at 5 tonnes ha^{-1} increased it by 42%. The organic source of SFM, as well as a lesser rate of inorganic (25 kg N ha^{-1}) resulted in considerably greater NUE than the untreated control, indicating that the soils required some fertility amendment. The rise in NUE owing to organic sources of soil amendment, particularly FYM, might be attributed to "FYM's low C/N ratio, which allows it to breakdown quickly and release plant-available nutrients". Farm Yard Manure (FYM) does this by increasing SOC, which is a significant indication of soil health, particularly in terms of crop fertility. This is in agreement with Thomas *et al.* (2019), who observed improved nutrient bioavailability as a result of SOM (soil organic matter) decomposition, as well as more mineral nutrient exchange sites, which boosted the soil's cation exchange capacity (CEC). On unfertilized soil, "SOC may give 90% plant available N, 80% plant available P, and 50% plant available S, as well as micronutrients" (Duxbury *et al.,* 1989).

The NUE value was affected differently depending on the inorganic source of N. NUE was enhanced by 41% when inorganic fertilizer was applied at 25 kg ha^{-1} (50% less than the recommended rate), while it was decreased when rates were greater than 25 kg N ha^{-1}, with the lowest value of NUE being achieved at 75 kg N ha^{-1} (which is 50% higher than the recommended rate). According to Nin *et al.* (2016), single mineral fertilization or over -

application accelerates the breakdown of SOM, resulting in deteriorated soil structure, decreased soil aggregation, and nutrient loss through leaching, fixation, and emissions of greenhouse gases. As a result, adopting a crop management strategy that has the ability to increase wheat NU_tE is critical in order to decrease N loss through leaching.

As a result, a long-term SFM strategy should be built around crops that can recycle or replenish nutrients through biomass or atmospheric N fixation. On this study, for example, no significant influence on NU_tE was observed when wheat was planted in plots previously occupied by potato, regardless of the SFM techniques used. The value of NU_tE, on the other hand, increased when the maximum amount of inorganic fertilizer (75 kg N ha^{-1}) was used.

When wheat was planted in untreated control (SFM1) plots with potato as a pre-crop, the NU_tE value was lowered (by 26 and 32%, respectively) when compared to dolichos lablab and green pea as pre-crops. Wheat treated with inorganic fertilizer (SFM5) at 50 kg N ha^{-1} in plots previously inhabited by dolichos lablab and green pea improved NU_tE value by 14 and 12%, respectively, in plots previously occupied by dolichos lablab and green pea. The ability of *T. aestivum* to use either the inherent or applied N was clearly increased when modest rates of inorganic fertilizers were used with legumes as pre-crops. Because legumes can repair atmospheric N_2 symbiotically, they only need a little amount of nitrogen fertilizer. With legumes as pre-crops, an application of inorganic fertilizer more than 50 kg N ha^{-1} decreased wheat's ability to use applied or inherent soil N (reduced NU_tE). This was further explained by the fact that most crops, particularly potato and other horticultural crops, deplete soil nutrients during their growth cycle, and some of these nutrients are harvested and depart the farm. The findings of this study contradict those of Rahimizadeh *et al.* (2010), who found that wheat cultivated after potato had higher NUE, NU_tE, and NU_pE. The differences between the two experiments might be due to the fact that they were done in different environments. It was also critical to notice that growing wheat following potato in a tropical setting with heavy rainfall may necessitate higher inorganic fertilizer rates on the preceding grain legume.

Aside from NUE and NU_tE, data on the influence of SFM methods on Nitrogen uptake efficiency (NU_pE) showed significant variations across the SFM treatments. Among the SFM methods tested, applying FYM at a rate of 5 t ha^{-1} resulted in a significantly higher NU_pE value than the untreated control. Organic sources of N, such as FYM (5 t ha^{-1}) and green manure (*L. trichandra* @2.5 tonnes ha^{-1}) raised NU_pE values by 80 and 71%, respectively, whereas the lowest rate of inorganic source of N (25 kg N ha^{-1}) increased NU_pE values by 75%. Omara *et al.* (2019) found poorer N absorption efficiency from organic sources than those acquired from inorganic N sources because the study utilized manure from beef animals (whose dung includes 0.57% N), but the current study used dairy cow manure (which contains 0.52% N). Green (2015) explains this variance by stating that the nutritional value of animal manures is more varied since it is impacted by the animal's diet. He also linked variances in animal dung to seasonal variations on and across farms, regions, and even on a broader global scale. Furthermore, it was clear that applying FYM resulted in greater NU_pE values than applying inorganic fertilizers at higher rates (N rates > 25 kg N ha^{-1}). As a result, when compared to higher rates of inorganic N sources, organic sources of N and the lowest inorganic source of 25 kg N ha^{-1} were more efficient in terms of NU_pE. This was further confirmed by the fact that the value of NU_pE decreased when the rate of inorganic N increased above 25gk N ha^{-1}. As a result, "organic based fertilizers allow the crop to recover more nitrogen than inorganic based fertilizers". This is because, according to the microbial N mining theory, N fertilizer reduces microbial mineralization of SOM, since microorganisms increase SOM breakdown in quest of N to fulfill energy demands for growth metabolism when soil inorganic N levels are low (Moorhead & Sinsabaugh, 2006). The succeeding cereal crop's N absorption efficiency would be decreased as a result of this procedure. As a result, increasing SOM inputs rather than decreasing SOM mineralization should be the goal of any SOM-increasing strategy. One way to attain this aim is to switch from synthetic nitrogen fertilizer to manure and legume sources of nitrogen. To summarize, the use of direct inorganic N sources should be minimized in order to attain sustainable N uptake efficiency, while the use of organic sources should be encouraged.

5.5 Effect of water harvesting on water use efficiency (WUE) of wheat

The use of water harvesting had little effect on WUE. Water harvesting is essential throughout the growing season and in situations where rainfall is scarce, since it provides strategic mitigation to crops by limiting water flow and allowing crops to improve WUE. Wiyo *et al.* (2000) and Howell *et al.* (2002) both explained this by stating that tie-ridges sustain higher levels and delay soil water loss. As a result, tie ridges (WH2) are a superior water harvesting strategy for increasing wheat WUE in dry seasons than flat (WH1) beds. This is consistent with the findings of numerous studies that show higher infiltration, rainfall usage efficiency, and soil water content, as well as better crop production, as a result of tie ridging (Wiyo *et al.,* 2000).

5.6 Effect of crop rotation on Water Use Efficiency (WUE) of wheat

Under rainfed conditions, water plays a critical role in agricultural development. Continuing population expansion, as well as the expected effects of climate change, such as precipitation fluctuations, exacerbate the water problem (Singh *et al.,* 2014). As a result, the judicious use of water for enhanced agricultural output necessitates effective water use, and therefore WUE. A variety of factors influence WUE, including meteorological circumstances, edaphic factors, plant type, and agronomic methods (Singh *et al.,* 2014). There are a variety of strategies for increasing WUE in a rain-fed ecosystem, but they are all dependent on the environment. In this study, four crop rotation systems were tested in a three-year cycle: wheat – dolichos – wheat, wheat – green pea – wheat, wheat – potato – wheat, and continuous wheat. In comparison to potato and continuous wheat, the effect of dolichos lablab as a pre-crop on WUE increased by 53% and 3%, respectively. Dolichos lablab's enhanced WUE value might be due to "its large root system and strong tap root, which have the potential to improve soil physical condition by breaking up hardpans and tapping moisture and nutrients from deep within the soil, therefore increasing soil moisture availability" (Valenzuela & Smith, 2002). During the fallow season, this helped to boost water and nutrients in the top soil, allowing the succeeding wheat crop to have more moisture accessible for use. These findings corroborate those of Thorup-Kristensen & Kirkegaard (2016), who found that previous crops and management had a substantial impact on water and nitrogen availability, particularly in soil layers deeper than one metre. The wheat WUE value found in this study is lower than that found by Zhang *et al.* (2016), who found that leguminous green manure (LGM) increased wheat WUE by 28% when compared to fallow management. It is possible that the variation in WUE value observed is due to the various legume species utilized in the prior and current studies. However, there were no significant variations in WUE value between green pea and wheat as pre-crops in this study.

When wheat was cultivated without fertilizer after dolichos lablab or potato, WUE values were higher than when green pea and wheat were used as pre-crops. However, wheat grown with FYM at 5 tonnes ha^{-1} on plots formerly occupied by green pea had a much higher WUE value than dolichos lablab or potato. These findings highlighted the relevance of green pea and organic fertilizer sources in improving wheat WUE. The increase in WUE observed when wheat was planted with organic fertilizer in a plot formerly occupied by legumes might be due to Dolichos lablab's complex tap root system, which could have absorbed moisture from the lower zones of the soil profile during fallow. This contributed to the accumulation of soil moisture during the fallow period, which may have improved the WUE of the succeeding wheat crop. This was in line with the findings of Zhang *et al.* (2016), who found that, despite roots accounting for just 10 - 20% of total plant weight, a well-developed root system is critical for nutrient and water absorption, as well as crop development and production. Furthermore, "improved root water and nutrient absorption capacity leads to increased production and water and nitrogen usage efficiency" (Feddes & Raats, 2004; Palta *et al.,* 2007). As a result, the moisture absorbed by dolichos lablab due to its large tap roots may have been kept by FYM, which increased the water holding capacity of soil under this wheat production system for the benefit of the subsequent wheat crop. The lowest WUE value reported following potato with green manure as SFM treatment might be due to the delayed release of nutrients from green manure, which may offer a chance to improve nutrient uptake, resulting in a higher NU_pE. The low WUE value might be due to the slow release of nitrogen and the buildup of biomass in the short term. In contrast, higher WUE owing to the highest rate of inorganic fertilizer (75 kg N ha^{-1}) may be attributed to an increase in above ground biomass due to the high rate of inorganic N. This is in agreement with Subhan *et al.* (2017), who found improved total dry matter, grain, and straw yields, as well as increased WUE due to the higher grain yield. When compared to potato as a pre-crop, wheat followed by dolichos lablab and green pea with the maximum rate of N (75 kg N ha^{-1}) resulted in an enhanced value of WUE (by 57 and 53%, respectively). As a result, increasing rates of inorganic fertilizer can improve wheat's capacity to use soil moisture more efficiently.

Wheat planted in tie ridged plots had a much greater influence on the WUE value than wheat planted in flat bed plots with dolichos lablab as a pre-crop. The effect of growing wheat on tie ridged plots following dolichos had a significant (15%) rise in WUE value. The increase in WUE due to tie ridging could be attributed to high rainfall during the previous season, which might have aided early growth for rapid ground cover and improved tolerance to high temperatures, thereby increasing WUE through reduced evaporation while increasing evapotranspiration for the benefit of the following wheat crop. This is consistent with Hatfield and Dold's (2019) discovery that increasing the amount of water lost in transpiration by employing genotypes with fast leaf development, denser planting, or fertilizers can enhance WUE through increasing ground cover. The benefits of tie ridges were more evident with a legume as a pre-crop, according to the findings of this study. This can be explained by the fact that legumes conserved moisture in the previous season as a result of biomass left on the plots' surface or absorbed into the soil. The presence of biomass from the previous legumes can also reduce soil temperature, lowering evaporation and boosting evapotranspiration, resulting in improved WUE.

When wheat was planted without fertilizer on plots that had previously been occupied by either green pea or wheat, the findings of the interaction effects of CR and SFM indicated considerably lower values of WUE. However, compared to where green pea and wheat were the pre-crops, growing wheat without fertilizer after dolichos lablab or potato dramatically enhanced WUE value. The lower WUE valuef achieved when wheat was not fertilized and was followed by green pea or wheat might be explained by the fact that the importance of legumes as pre-crops on the succeeding wheat crop is legume species specific and requires some type of starting soil amendment. While planting wheat after wheat with 5 tonnes ha^{-1} FYM resulted in a significantly better WUE value than planting wheat with the same quantity of FYM but before green pea or dolichos lablab as well as potato. Green manure (*L. trichandra*) was utilized as a SFM strategy in plots previously occupied by Dolichos lablab, and it resulted in a substantially higher WUE than green manure used in plots previously occupied by wheat or green pea. Wheat planted after potato with green manure, gave the lowest WUE value. When the maximum amount of inorganic fertilizer (75 kg N ha^{-1}) was utilized on plots previously occupied by dolichos lablab, green pea, and wheat compared to potato as the preceding crop, the value of WUE rose. In comparison to potato as a pre-crop, wheat preceded by dolichos lablab (Sitienei *et al.,* 2017) and wheat with the maximum rate of N (75 kg N ha^{-1}) resulted in a higher WUE value. As a result, a higher rate of inorganic fertilizer is required to accelerate wheat's capacity to better utilize soil moisture. This is in agreement with numerous authors who found that when N application rates are higher than the optimum required by crops, the WUE may increase, but the danger of Nitrate-N leaching and the quantity accumulating below the root zone may also increase (Ullah *et al.,* 2019).

When wheat was planted in tie ridged (WH2) in plots previously occupied by dolichos lablab, the cumulative impact of interaction between CR and WH showed substantially greater WUE than when wheat was cultivated in a flatbed (WH1) in plots previously occupied by dolichos lablab. The benefits of tie ridges were more evident with a legume (Dolichos lablab) as a pre-crop, according to the findings of this study and as confirmed the results reported by Stagnari *et al.* (2017). This can be explained by the fact that legumes conserved moisture in the previous season as a result of biomass left on the plots' surface or absorbed into the soil. "The presence of biomass from the previous legumes can also reduce soil temperature, lowering evaporation and boosting evapotranspiration, resulting in improved water use efficiency (WUE)".

To recapitulate, cultivating the grain legume crop is a better alternative than potato and continuous wheat in Njoro Sub-county for improving the productivity and WUE of the subsequent wheat crop while also maintaining the soil water balance in rainy years.

5.7 Effect of soil fertility management on water use efficiency (WUE) of wheat

Soil fertility management (SFM) has a significant impact on wheat WUE, regardless of whether the source is inorganic or organic. These findings backed up the idea that improving soil fertility is important for crops or plants to make optimal use of water. This is consistent with the findings of Subhan *et al.* (2017), who found that applying either inorganic or organic fertilizer types enhanced WUE. Inorganic sources of SFM strategies, on the other hand, have a higher effect than organic sources. The same author also reported that the inorganic fertilizer had a substantially higher WUE than the NPK fertilizer because of the increased grain yield. With the maximum rate of inorganic N fertilizer (75 kg N ha^{-1}), the highest WUE value was reached, although green manure application also produced a high WUE value. Although inorganic N sources provided higher WUE than organic sources, organic N sources had a competitive advantage in terms of wheat yield sustainability.

When compared to applying inorganic fertilizers separately, manure improves soil nutrient balance, soil structure, and moisture-holding capacity, as well as facilitating environmental protection (Conacher & Conacher, 1998; Geng *et al.,* 2019). Organic fertilizer application is an effective way to sustain crop yields and SOC stocks (Manna *et al.,* 2007). Soils in Njoro Sub-County are generally low in organic matter (less than 4%), and adding organic matter and other organic sources to the soils might help them last longer. Although inorganic fertilizer appears to be a highly rapid and effective remedy, the energy cost is quite expensive, and there are numerous environmental problems. Because organic N sources have the ability to maintain soil fertility for increased wheat yields, small-scale wheat producers in Njoro Sub-County can readily adapt to their use.

5.8 Effect of water harvesting on wheat yield and biomass

Water harvesting (WH) had no significant effect on wheat production or biomass. The seasonal rainfall was sufficient to meet the wheat crop's yearly water demand of 600 mm (Doorenbos *et al.,* 1992). These findings corroborate those of Wiyo *et al.* (2000), who advocated that rainfall of more than 900 mm (normal and wet years) would be adequate to fulfill crop water requirements (CWR) without tie-riding, obviating the need for them. To summarize, rainfall patterns in Njoro Sub-County have become more unpredictable than ever before, necessitating certain agronomic management system adjustments to mitigate the current rainfall patterns (MoALF, 2016). In order to sustain wheat production in this region, various water collection techniques, such as tie ridges, must be used, especially when wheat is sown during the second season (September – November). Otherwise, flatt beds should be utilized instead of tie ridges during years with regular rainfall (over 500 mm).

5.9 Effect of crop rotation (Pre-crop) on wheat yield and biomass

Crop rotations (CR) and their impact on N usage efficiency have resurfaced as a result of the shift toward sustainable agriculture. This study was undertaken to assess the advantages of crop rotation (pre-crop) on wheat grain production in an attempt to respond appropriately to the shift toward sustainable crop productivity. Crop rotation (CR) had a substantial impact on wheat yields, according to the findings. In the short crop rotation (CR) cycle, wheat was preceded by dolichos lablab and green pea, yielding much more than potato and continuous wheat. Dolichos lablab and green pea as pre-crops improved wheat production by 92 and 73%, respectively, as compared to potato. Dolichos lablab contributed more to the grain legumes than green pea as a pre-crop, according to the results. While the improvement in wheat grain production owing to the two legumes (dolichos lablab and green pea) as pre-crops outperformed those achieved with wheat and potato. Evans *et al.* (2003) found that grain legumes, green pea, and vetch (*V. sativa*) silage crops improved wheat production by 3.5 – 4 tonnes ha^{-1} when compared to continuous wheat yield. The observed advantage of legumes as pre-crops might be attributed to legumes' contribution of N fixation and increased soil organic matter, which could have retained the fixed

N and therefore reduced the risk of leaching. Through symbiotic relationships, legumes fix atmospheric nitrogen, delivering 50% of the nitrogen utilized in agriculture production systems (Graham & Vance, 2003). This is in addition to the residual nitrogen left in the soil for subsequent non-legume crops (Dhakal *et al.,* 2016 Peoples *et al.,* 2009). This demonstrates the enormous potential of legume crops as soil restorers, stabilizers, and yield enhancers. Berg (1997), for example, noted that wheat yields were much greater after alfalfa and milk vetch than grass. The involvement of both nitrate sparing by legume species and mineralization of N-rich wastes explains this improvement (Evans *et al.,* 1991).

The impact of CR (Pre-crop) on biomass was also investigated. As a consequence of the findings of this study, crop rotation had a substantial impact on biomass in addition to wheat production (CR). Wheat biomass was higher when it was preceded by dolichos lablab, green pea, or even continuous wheat than when it was preceded by potato. Dolichos lablab and green pea, among the legume pre-crops, produced significantly more biomass than when potato was the predecessor crop. In comparison to potato as a pre-crop, the increase in biomass value after either dolichos or green pea was around 90%. The fact that grain legumes are good pre-crops for cereals may explain the role of legumes as a preceding crop to cereals in the buildup of biomass. However, the capacity of legumes to fix atmospheric nitrogen varies by species. These findings correspond with those of Kaul (2004), who found that high nitrogen residues left by legumes after harvest as residual soil mineral N (SMN) as well as in organic crop residues contributed significantly to the crop density (biomass) of succeeding crops. Adeleke & Haruna (2012) explained the findings of this study by observing higher Cation Exchange Capacity (CEC) on plots previously cropped to legumes compared to plots previously occupied by maize and fallow plots, and attributed the observation to leaf litter droppings, which acted as mulch and later decomposed to add nutrients to the soil.

Furthermore, using legumes as a pre-crop for cereals (wheat) has a significant impact on grain output and biomass buildup. It's also worth noting that the two legumes tested in this study had varied capacities when it came to increasing wheat production and above-ground biomass. Although dolichos lablab produced greater grain yield and biomass than green pea, its poor performance in high rainfall locations allows the latter to be suggested as a wheat pre-crop. Green pea should be sown during the short-wet season for optimum advantage as a pre-crop, with wheat following in the long rainy season.

5.10 Effect of the soil fertility management (SFM) on yield and biomass of wheat

Soil fertility management (SFM) had a substantial impact on wheat production, and it was clear that wheat planted without fertilizer (the untreated control) yielded much less grain than the treated plots. The use of inorganic N sources resulted in higher grain yields when compared to organic fertilizers. For example, compared to FYM at 5 tonnes ha^{-1} and green manure (*L. trichandra*) at 2.5 tonnes ha^{-1}, the maximum rate of N (75 kg N ha^{-1}) improved production by 38 and 22%, respectively. In comparison to organic sources, the application of inorganic fertilizer at the maximum rate (75 kg N ha^{-1}) resulted in the highest wheat production. This might be due to the fact that the organic material mineralized too quickly for the nutrients to become accessible in time for wheat production to rise during a three-season timeframe. Instead, the use of a high inorganic N fertilizer resulted in better wheat yields. This is consistent with Mahal *et al.* (2019), who found that increased N availability from high N fertilizer inputs and associated legume biomass raised total soil N to the point where it no longer hindered microbial activity.

When it came to wheat biomass, there was no discernible difference in the usage of inorganic and organic fertilizers. Green manure (*L. trichandra*) applied at 2.5 tonnes ha^{-1} (27.75 kg N ha^{-1} equivalent) increased biomass by 42%. Furthermore, compared to the untreated control, the application of green manure at 2.5 tonnes ha^{-1} of SFM boosted biomass by around 13%. These findings are consistent with those of Agegnehu *et al.* (2014), who found that inorganic and organic nutrients, either alone or in combination, had a substantial impact on wheat grain production and total biomass. Other research have found that green manure increases wheat grain production, owing to improved soil characteristics and substantial N recoveries from the green manure (N'Dayegamiye & Tran, 2001). Green manure has also been linked to higher cereal grain yields. Treatments with solitary application of Tithonia, Calliandra, and Leucaena, for example, reported greater maize yields than the inorganic fertilizer treatment (Mugwe *et al.,* 2007). As a consequence of the findings of this study, it is clear that soil fertility techniques are required, but that organic sources of N fertilizer are more successful in increasing grain production and biomass.

5.11 Interaction effect of crop rotation (CR) and soil fertility management (SFM) on nitrogen use efficiency (NUE) and nitrogen uptake efficiency (NU_pE) of wheat

Crop rotation (CR) and soil fertility management (SFM) in combination have a substantial impact on NUE. The highest value of NUE was obtained when wheat was fertilized with FYM at 5 t ha^{-1} on plots that had previously been occupied by green pea in the previous season (87.5%), while the lowest value of NUE was reported when FYM and potato as a pre-crop were used. Because legumes are capable of fixing atmospheric nitrogen while also releasing high-quality organic matter in the soil to improve soil nutrient circulation and water retention, FYM and green pea as a pre-crop have a higher value (Stagnari *et al.,* 2017).

While the FYM applied after the green pea crop in the rotation may have released some N into the soil, it is possible that some of it was kept for the benefit of the following crop. According to a previous research by Muhammad *et al.* (2017), FYM supplied a considerable quantity of nitrogen to the soil (range from 51 to 53 kg N ha^{-1}). When wheat was planted with FYM on plots previously inhabited by green pea, the NUE value was substantially greater than when wheat was planted with FYM on plots previously occupied by dolichos lablab. Other researchers have shown that legumes are important for long-term wheat production, although the extent of their impact on NUE varies by species (Muthuri, 2013). The relevance of legumes in crop rotation confirms this reality, as the challenge in rain-fed areas is to enhance wheat profitability by lowering production costs and developing more sustainable production techniques. Previous research has shown that including legumes into crop rotations has the potential to enhance available N for cereals at a reasonable cost (Espinoza *et al.,* 2012). While the presence of legumes in a cropping sequence has been linked to a variety of advantages, including improved soil quality, porosity, and structure (McCallum *et al.,* 2004). To explain the advantages of incorporating legumes in the short rotation, Kirkegaard *et al.* (2008) and Osborne *et al.* (2010) demonstrated that legumes in the rotation impact certain microorganism populations in the rhizosphere for the benefit of following crops. As a result of the findings of this study, it is possible to increase *T. aestivum* production by employing a short-term legume–cereal rotation system.

Inorganic fertilizers applied to plots formerly inhabited by different crops (dolichos lablab, green pea, potato, and wheat) showed an interaction impact on NUE. On plots formerly occupied by green pea, for example, the second greatest mean value of NUE was obtained with the lowest rate (25 kg N ha^{-1}) of inorganic fertilizer. Previous research has indicated that post-legume cereal yields are typically 40-80% higher than cereal yields without N fertilizer, resulting in an extra 450-1000 kg of grain per hectare across a variety of settings (Hayat & Ali, 2010; Seymour *et al.,* 2012). The claimed yield benefit is due to the fact that legumes in crop rotation are a low-cost means of boosting available N supply for cereals (Espinoza *et al.,* 2012). In addition, including legumes in a cropping sequence can improve soil quality, porosity, and structure (Rochester *et al.,* 2001) as well as influence specific microorganism populations in the rhizosphere (Kirkegaard *et al.,* 2008; Osborne *et al.,* 2010) for the benefit of subsequent crops.

Nitrogen uptake efficiency (NU_pE) was strongly affected by the interaction of CR and different SFM methods. When FYM was used as an amendment on plots previously occupied by dolichos lablab and green pea, NU_pE levels were greater than when potato and wheat were used as pre-crops. Similarly, when the lowest rate of inorganic fertilizer source (25 kg N ha^{-1}) was administered to plots previously inhabited by green pea than dolichos lablab, potato, and wheat, a greater value of NU_pE was detected. These findings demonstrated the relevance of legumes as pre-crops, since their inclusion in crop rotation systems improved the succeeding wheat crop's ability to absorb more N when compared to higher inorganic N rates. Stagnari *et al.* (2017) revealed in a review paper that legumes release high-quality organic matter in the soil and improve soil nutrients circulation and water retention as a result of their ability to fix atmospheric nitrogen. It is also clear from the results that utilizing FYM as a soil amendment on plots that had previously been inhabited by green as well as dolichos lablab as pre-crops improved the benefit of legumes on NU_pE in the rotation system more than using potato and wheat as pre-crops. Farmyard manure (FYM) is a beneficial organic fertilizer for sustaining soil fertility in alternative agricultural systems.

The relevance of FYM in helping to improve N availability might be linked to its involvement in increasing the availability of phosphorous, which is a key component in atmospheric N fixation. This is also corroborated by Jarvan *et al.* (2017), who observed enhanced phosphorous availability as a result of FYM application. In the humid tropics, the practice of utilizing legumes in rotation with wheat for increased Soil-N delivery and insect, disease, and weed-break impacts should be encouraged (Danga *et al.,* 2009). Therefore, the use of legumes in wheat-based cropping is a realistic option for resource-poor small and medium-scale farmers in Africa, notably in the Njoro sub-county where this study was performed, to reduce inorganic fertilizer usage.

5.12 Interaction effect of crop rotation (CR) and water harvesting (WH) on water use efficiency (WUE)

Water use efficiency (WUE) is one among the important parameters within the current times of unreliable rainfall within the former high rainfall areas of Kenya. “Planting wheat on tie ridged (WH2) plots that were previously occupied by dolichos gave significantly higher WUE than when planting was done on flat beds (WH1)”. However, planting after garden pea didn't influence WUE regardless of the water management strategy (either flatbed = WH1 or tie ridges = WH2). This reveals that although legumes are important components in crop rotation systems, their contribution towards WUE might be variable supported by the species. During this study, the results demonstrated that growing wheat after dolichos on tie ridged plots gave higher WUE value than when garden pea was used as a pre-crop. The superior trait observed on the power of hyacinth bean with reference to the WUE of garden pea in tie ridged plots might be due to its extensive root systems.

Similar trend was observed on the value of WUE when green pea was grown after potato. However, under continuous wheat a significantly higher value of WUE was observed on flatbeds than tie ridges. The advantage of increased WUE when wheat was planted on tie ridged plots after hyacinth bean might be attributed to the very fact that a neighborhood from fixing atmospheric N and releasing within the soil high-quality organic matter may need enhanced soil nutrients’ circulation and water retention. The top quality soil organic matter released to the soil by legumes (in this case dolichos lablab) as pre-crops have the potential to carry soil moisture for the advantage of subsequent crops in terms of enhanced soil moisture. These observations are in agreement with Stagnari *et al.* (2017), who reported that legumes have the potential to repair the atmospheric nitrogen, release within the soil high-quality organic matter and while at an equivalent time facilitate soil nutrients’ circulation and water retention in cropping systems.

The results obtained during this study, generally revealed that the advantage of tie ridges was more pronounced with a legume as a pre-crop. This will therefore be attributed to the very fact that legumes within the previous season would have conserved moisture due to the biomass left on the surface of the plots or incorporated into the soil. The presence of biomass from the preceding legumes also can lower the soil temperature hence reducing evaporation and instead increasing evapo-transpiration thereby enhancing water use efficiency (WUE).

In the current global climate change scenario, "the simplest performing system under legumes as pre-crops and water harvesting strategies that help to retain moisture for relatively longer period could also be the simplest practice". This is able to have a comparative advantage because by retaining moisture for a protracted period would enhance the power of wheat to become more efficient in utilizing moisture. This was confirmed by the results of this study and would therefore form the idea of formulating the advice for the management of N to reinforce its uptake efficiency subsequently leading to NUE.

5.13 Interaction effect of crop rotation (CR) and soil fertility management (SFM) on water use efficiency (WUE)

Significantly higher WUE were observed when wheat was planted without soil fertility amendment (untreated control) on plots that were previously occupied by either dolichos lablab or potato than when the plots had been under green pea or continuous wheat. The contribution of legumes especially dolichos lablab on WUE might be because of its elaborate tap root that would have increased the capacity to access moisture from lower depth within the profile hence enhancing faster above-ground cover hence reducing evaporation.

Previous studies have reported that in environments with sufficient rainfall before the season, root depth represents the key trait for the exploration of stored water, especially in fine soils (Tron *et al.,* 2015). The accumulated biomass may need also helped to create increased stock of soil organic matter that would have successively held moisture for the advantage of the next crop of wheat. The moisture embedded within the soil organic matter released slowly to be used by the next crops would enhance WUE. The importance of soil organic matter as a key component within the soil moisture accumulation has been emphasized by several workers. for instance , SOM decline can reduce soil water retention (SWR) (Johnson *et al.,* 2009; Kibblewhite *et al.,* 2008) by up to 10% for a difference in SOM content from 7 to 3% (Gregory *et al.,* 2015).

The results showing increased WUE value when wheat was grown without fertilizer following hyacinth bean or potato as pre-crops offers a chance to mitigate against the consequences of variable weather patterns currently occurring in Njoro Sub-county. This advantage of dolichos lablab and potato as pre-crops might be due to the biomass attained by the preceding crops which may have reduced evaporation and instead enhanced evapo-transpiration hence WUE. Similar trend was observed when wheat was preceded by either dolichos lablab or garden pea and treated with highest rate of inorganic fertilizer (75 kg N ha^{-1}). The benefit accruing from this might even be attributed to the residual clay moisture thanks to the preceding legumes dolichos lablab or green pea) and extra moisture conserved because application of high N rate that helped to market early crop cover hence prompting increase of WUE.

Planting wheat after wheat with FYM at 5 tonnes ha^{-1} resulted during a significantly higher WUE value than within the situation where wheat was planted with same amount of FYM but preceded by garden pea and hyacinth bean also as potato. Manure as a SFM strategy and dolichos lablab as a pre-crop resulted during a significantly higher WUE than manure and wheat or green pea. However, lowest value of WUE was observed when wheat was grown after potato with manure. This therefore demonstrates the importance of organic sources of soil fertility amendments with legumes as pre-crops in enhancing WUE. During this study, the contribution of organic sources of fertility (FYM and green manure) and green pea and hyacinth bean as pre-crops are observed on WUE. The many contribution observed might be due to the biomass derived from the legumes and cemented further by organic fertilizers resulting from either FYM or manure. The biomass may have also contributed to the increased pool of SOC that would have also held moisture for an extended time making it available to the next crop and enhancing its WUE.

The highest rate of inorganic fertilizer (75 kg N ha^{-1}) and dolichos lablab as a pre-crop increased the worth of WUE, and therefore the same trend was also observed with green pea and wheat as pre-crops compared to when potato was the preceding crop. Similarly, wheat preceded by dolichos lablab and green pea with the very best rate of N (75 kg N ha^{-1}) resulted during a higher value of than potato as pre-crop. These results demonstrate the importance of inorganic source of N in increasing the power of legumes to reinforce the power of the next crop to utilize soil moisture more efficiently. This will be attributed to the very fact that the inorganic N is quickly available thus promotes the faster growth of the above ground biomass hence contributing to the buildup of SOM. The increased SOM could have helped to carry soil moisture for relatively longer time allowing the next crop (wheat) to efficiently utilize it. Whereas soil water storage within the profile during the fallow period has been a crucial consideration in land agriculture where water is usually limiting crop yields, the growing of a short-term legume in rotation with cereal during a humid climate, and its depletion of fallow water doesn't adversely affect yield of following cereal crop mainly due to adequate rainfall during the most season for wheat (Danga *et. al.,* 2009). This scenario is vital to notice because within the humid environment the growing of legumes as pre-crops with increased inorganic N would contribute towards increased moisture for the next crops due to enhanced above ground biomass and increased SOC thereafter. These results accept as true with Stagnari *et al.* (2017), who from a review reported that legumes, among other benefits, increase soil organic matter while facilitating soil nutrients' circulation and water retention. These attributes are extremely important within the consideration for designing sustainable soil and water management strategies with a view to enhancing nutrients and water use efficiency.

5.14 Interaction effect of water harvesting (WH) and soil fertility management (SFM) on water use efficiency (WUE)

In general, a relationship between WH and SFM had a substantial influence on WUE. The WUE value of wheat planted without fertilizer on tie ridged (WH2) plots was substantially greater than that of flatbeds (WH1). These results might be explained by the fact that the tie ridged plots were able to hold rainwater and so increase infiltration. This also allowed crops on tie ridges to have access to additional soil moisture, allowing for higher WUE. These findings are consistent with those of Behera & Sharma (2014), who found that planting wheat on furrow – irrigated raised-bed and broad-bed and furrow (BBF) – gave higher WUE than planting wheat on flatbed (FB). However, planting on flatbeds with FYM at 5 tonnes ha^{-1} as a soil fertility management approach resulted in a greater WUE than under tie ridged plots. This highlighted the relevance of soil fertility management techniques, particularly organic sources (e.g. FYM), in assisting soils in holding and conserving rainwater trapped by tie ridges. These findings are consistent with previous research by Singh *et al.* (2015), who found that adding manure and maintaining crop residues, among other practices, improved soil structure, increasing water infiltration into the rooting zone of crops and reducing evaporation losses, resulting in increased rain-fed crop productivity. As a result, considering the use of FYM on plots with water collection for enhanced water usage efficiency and long-term crop yield is critical.

When green manure (SFM3) at 2.5 tonnes ha^{-1} (equal to roughly 25 kg N ha^{-1}) was used to fertilize wheat on tie ridged (WH2) plots, greater WUE was achieved than when flatbeds were utilized. When the crop was planted on flatbeds rather than tie ridged plots, the value of WUE was greater at the lowest rate of inorganic N (25 kg N ha^{-1}). Despite this, the value of WUE rose as the amount of inorganic N applied increased, peaking at the maximum rate (75 kg N ha^{-1}) of inorganic N application. These findings show that, while tie ridges are crucial for boosting soil moisture storage and therefore raising WUE, the advantages of external N addition from organic or inorganic sources can be amplified. This might be because applying N to crops causes them to grow quicker, increasing above-ground biomass and lowering direct evaporation while boosting WUE. These findings are consistent with those of Subhan *et al.* (2017), who found considerably increased total dry matter, grain, and straw yields as a result of inorganic fertilizer treatment, as well as higher grain yield and WUE. Furthermore, they discovered that plots treated with mineral and organic fertilizers had greater WUE in terms of grain production. Other researchers have confirmed these findings, reporting varied advantages of inorganic and organic N sources on WUE. For example, Subhan *et al.* (2017) found that using N fertilizer enhanced the efficiency of water use by wheat, but Yassen *et al.* (2006) found that bovine dung had a more noticeable effect on increasing the WUE of grain crops when compared to composted sunflower waste. As a result, WUE is improved when wheat is planted on tie ridged plots that are treated with either an inorganic or organic source of nitrogen. Finally, given the current state of climate change, organic N sources in plots with water-harvesting features like tie ridges would be preferable.

5.15 Interaction effect of crop rotation (CR) and soil fertility management (SFM) on yield

Regardless of the previous crop, this study found clear evidence that a high rate of inorganic N source resulted in considerably better production. The higher production due to legumes as pre-crops and the application of the greatest rate of inorganic N fertilizer might be ascribed to the fact that the high rate of inorganic N increased the biomass of the pre-crop, resulting in increased yield of the following wheat crop. Integrated Soil Fertility Management (ISFM) alternatives have been proposed by several studies for increasing soil fertility and agronomic effectiveness of applied inputs (Sanginga & Woomer, 2009; Vanlauwe *et al.,* 2010). Furthermore, for the most efficient use of organic and inorganic resources and crop yield, ISFM techniques including both organic and inorganic resources in an integrated way are critical (Verde *et al.,* 2013). To summarize, legumes, particularly dolichos, should be used as a pre-crop with an enhanced rate of inorganic N in short-term rotations to boost grain production and above-ground biomass buildup.

5.16 Interaction effect of water harvesting (WH) and soil fertility management (SFM) on yield

Due to an interaction between water harvesting (WH) and soil fertility management, a substantial interaction impact on wheat production was discovered (SFM). The impact of soil fertility management method and water management on yield was considerably ($p < 0.05$) larger in the tie ridge under unfertilized control (SFM1) than in normal ridges, according to the current study. Wheat fertilized with FYM at 5 tonnes ha^{-1} (SFM2) on tie ridged plots (WH2) yielded substantially ($p < 0.05$) less than the mean and the other SFM methods, with the exception of the unfertilized control (SFM1). However, the highest grain production was reported when wheat was cultivated with 75 kg N ha^{-1} inorganic nitrogen fertilizer (SFM6). These findings show that regardless of the N source, the impact of N to boosting grain production is significant. It's also worth noting that, independent of water collection technique, the greatest rate of N (SFM6; 75 kg ha^{-1}) resulted in considerably higher yields than the other soil fertility management options (in either flat bed or tie ridges).

However, the highest grain production was reported when wheat was cultivated with 75 kg N ha^{-1} inorganic nitrogen fertilizer (SFM6). These findings show that regardless of the N source, the impact of N to boosting grain production is significant. It's also worth noting that, independent of water collection technique, the greatest rate of N (SFM6; 75 kg ha^{-1}) resulted in considerably higher yields than the other soil fertility management options (in either flat bed or tie ridges). Several employees in arid regions of the world have reported the advantages of tie ridges. Tie ridges, for example, have been shown to increase crop yields when used as an in-situ soil and water conservation strategy (Temesgen *et al.,* 2012). While tie ridging is known to assist reduce runoff by holding rain water on the soil and allowing it to penetrate, it is also important in decreasing runoff (Zeyege *et al.,* 2015). Thus, tie ridging may be used in Nakuru County, particularly if wheat must be cultivated during the low and unpredictable second rains.

5.17 Interaction effect of crop rotation (CR) and water harvesting (WH) on yield

Wheat yielded more than other pre-crops when planted on tie ridged (WH2) plots that had previously been occupied by legumes (dolichos lablab and wheat). Wheat planted on tie ridged (WH2) plots that had previously been occupied by potato and yielded the lowest grain yield. Under the flatbed method, wheat grain production improved by around 16 percent when it was preceded by dolichos lablab and grown under tie ridge. This demonstrates that combining legumes as pre-crops with a tie ridge results in high wheat grain production. Other workers have mentioned the benefit of ridging. In Pakistan, for example, Hussain *et al.* (2018) observed a 23% increase in wheat output owing to ridge planting. This might be explained by the fact that the biomass produced by legumes may have conserved moisture for the benefit of succeeding crops.

Several researchers have cited the advantages of incorporating legumes in crop rotations. Legumes-based systems increase numerous elements of soil fertility, including SOC and humus content, as well as N and P availability (Jensen *et al.,* 2012). The yield attained in continuous wheat and flatbed plots, on the other hand, was higher than in tie ridged plots. The yield attained in continuous wheat and flatbed plots, on the other hand, was higher than in tie ridged plots. Because of the difficulties that rain-fed agriculture faces across the world, the findings of this study are extremely important.

The globe is currently experiencing a water crisis, with little room for large-scale irrigation growth. As a result, better water management in rain-fed agriculture is required not just to secure the water required for food production (Molden *et al.,* 2007), but also to create resilience to future water-related risks and uncertainties (Rockström *et al.,* 2010). However, because some experts expect a further reduction in rainfall and amplification of severe events (IPCC, 2007), it is critical to embrace integrated water harvesting (tie ridging) and crop rotation incorporating short-term legumes in regions like Njoro Sub-County to boost wheat output.

CHAPTER SIX
CONCLUSIONS, RECOMMENDATIONS AND NEW KNOWLEDGE

6.1 Conclusions

Crop rotation (CR), water harvesting (WH) techniques, and soil fertility management (SFM) were studied individually and in combination to assess their impacts on nitrogen use efficiency (NUE), water use efficiency (WUE), and wheat performance. The study's objectives were satisfied as a consequence of the findings, and the following conclusions were reached:

Objective 1: To determine the effect of crop rotation (CR) on nitrogen use and water use efficiency of wheat.

i) The most important factors in boosting NUE and WUE were legume pre-crops, especially when combined with SFM.

Objective 2: To determine the effect of soil fertility management (SFM) strategies on nitrogen and water use efficiency of wheat

i) Wheat NUE was favourably impacted by soil fertility management (SFM), particularly organic sources, but the effect was amplified when CR was added.

ii) Wheat NUE increased when the rate of inorganic fertilizer was reduced with legumes as pre-crops.

iii) Wheat on flat beds with an organic fertilizer source (FYM) had a higher WUE.

Objective 3: To determine the effect of water harvesting strategies on nitrogen and water use efficiency of wheat.

i) Except when combined with SFM and CR, the water harvesting (WH) approach had no impact on NUE and its related characteristics (NU_tE and NU_pE).

ii) On flatbeds, the application of organic fertilizer sources, particularly FYM, boosted WUE (WH1).

Objective 4: To determine the effect of rotation on the overall productivity of wheat.

i) In the context of appropriate soil and water management, crop rotation (CR) is a significant element in wheat production.

ii) In a wheat cropping system, legumes as a pre-crop have the potential to improve wheat grain production and biomass.

6.2 Recomendations

Based on the conclusions discussed according to the objectives some of the recommendations are as follows:

Recommendation for further research:

i) An examination of a broader range of grain legume species to assess their influence on wheat NUE and WUE.

ii) To determine the land equivalent ratios (LERs) and conduct a cost-benefit analysis of several legume species in Njoro wheat-legume cropping systems.

iii) Examine the wheat-legume farming system under pure organic conditions.

Recommendation for the farmers:

i) Wheat should be planted with FYM at 5 tonnes ha^{-1} in plots previously occupied by green pea to maximize NUE in short term rotation systems.

ii) To enhance wheat production, grain legumes should be planted before wheat in short legume – cereal rotation systems.

iii) As a short and long-term fertilization plan, a low dose (25 kg N ha^{-1}) of inorganic source in conjunction with legumes is advised to enhance NUE value of wheat and sustainable resource usage.

iv) During the main season with heavy rainfall, FYM at 5 tonnes ha^{-1} on flat beds is adequate to optimize WUE of wheat.

v) Wheat should be sown after green pea to increase grain production and above-ground biomass buildup.

vi) To optimize the benefits of green pea as a pre-crop, it should be planted during the short rainy season, with wheat following in the long wet season.

6.3 New knowledge contributed by the study

- It was learnt from this study that wheat in Njoro Sub-County should be planted on flat beds and planting wheat on tied ridges is not appropriate for Njoro especially during the main season when rainfall is high.
- Use of wheat – legume – wheat crop rotation will allow reduced use of inorganic fertilizers to as low as 25 kg N ha^{-1} or organic sources (green manure at 25 tonnes ha^{-1} or FYM at 5 tonnes ha^{-1}) and retaining the same yield levels. This will benefit wheat farmers interested in organic farming.

REFERENCES

Adeleke, M.A., & Haruna, I.M. (2012). "Residual Nitrogen Contributions from Grain Legumes to the Growth and Development of Succeeding Maize Crop", *International Scholarly Research Notices*, Article ID 213729, 5 pages, https://doi.org/10.5402/2012/213729.

Africafertilizer.org. (2016). *The Joint Countrystat Fertilizer Technical Working group (FTWG) fertilizer pre-validation workshop for Kenya, Tanzania and Ethiopia*. Held between 3rd and 4th October 2016, Dar-es-Salaam, Tanzania. http://africafertilizer.org.

Agegnehu, G., van Beek, C., & Bird, M.I. (2014). Influence of soil fertility management in wheat and tef productivity and soil chemical properties in the highland tropical environment. *Journal of Soil Science and Plant Nutrition,* 14, 532-545.

http://dx.doi.org/10.4067/S0718-95162014005000042**.**

AgraTronix™ MT-PRO™. Portable moisture Tester. Schuyler, Nebrasak, 68661, USA.

Alexandratos, N., & Bruinsma, J. (2012). World agriculture towards 2030/2050. ESA Working Paper No. 12-03. *Agricultural Development Economics Division, FAO, Rome*.

American Association of Cereal Chemists (2000). Approved Methods of the American Association of Cereal Chemists. AACC, St Paul, Minnesota (2000).

Anas, M., Liao, F., Verma, K.K., Sarwar, M.A., Mahmood, A., Chen, Z.L., Li, O., Zeng, X.P., Liu, Y. & Li, Y.R. (2020). Fate of nitrogen in agriculture and environment: agronomic, eco-physiological and molecular approaches to improve nitrogen use efficiency. *Biological Research,* 53**,** 47. DOI - 10.1186/s40659-020-00312-4

Anderson, J.M., & Ingram, J.S.I. (1993). Tropical Soil Biology and Fertility. *A handbook of methods, 2nd Ed.,* CAB International, Wallingford, UK.

Anonymous. (1997). Water harvesting and soil moisture retention. *A Manual on Small – scale and Sustainable Agriculture in the Tropics, Agromisa, Wageningen, The Netherlands.* pp. 9.

Askegaard, M., Plesen, J.E., & Kistensen, K. (2006). Nitrate leaching from organic arable crop rotations: Effects of location, manure and catch crop. *Soil Use and Management*, 21(2):181-188. DOI:10.1111/j.1475-2743. 2005.tb00123. x.

Asplund, L., Bergkvist, G., & Weih, M. (2014). Proof of concept: nitrogen use efficiency of contrasting spring wheat varieties grown in greenhouse and field. *Plant and Soil,* 374, 829-842. http://dx.doi.org/10.1007/s11104-013-1895-6

Aulakh, M.S., & Malhi, S.S. (2004). Fertilizer nitrogen use efficiency as influenced by interactions with other nutrients. In: *Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment (Editors: A.R. Mosier, J.K. Syers and J.R. Freney),* pp. 181-191. Island Press, Washington, USA.

Badaruddin, M., & Meyer, D.W. (1994). Grain legume effects on soil nitrogen, grain yield, and nitrogen nutrition of wheat. *Crop Science Journal,* 34, 1304 - 1309.

Bagayako, M., Buerkert, A., Lung, G., Bationo, A., & Romheld, V. (2000). Cereal/Legume rotation effects on cereal growth in Sudano-Sahelian West Africa: soil mineral nitrogen, mycorrhizae and nematodes. *Plant and Soil,* 218, 103–116.

Bai, C.H., Liang, Y.L., & Hawkesford, M.J. (2013). Identification of QTLs associated with seedling root traits and their correlation with plant height in wheat. *Journal of Experimental Botany,* 64, 1745–1753.

Baligar, V. C., Fageria, N. K., & He, H. (2001). Nutrient use efficiency in plants. *Communications in Soil Science & Plant Analysis*, 32, 921–950.

Barraclough, P.B., Howarth, J.R., Jones, J., López-Bellido, R., Parmar, S., Shepherd, C.E., & Hawkesford, M.J. (2010). Nitrogen efficiency of wheat: genotypic and environmental variation and prospects for improvement. *European Journal Agronomy,* 33, 1–11. DOI: 10.1016/j.eja.2010.01.005.

Basso, B., Sartori, L., Bartoco, M., & Cammarano, D. (2011). Economic and environmental evaluation of site-specific tillage in a maize crop in NE Italy. *European Journal of Agronomy,* 35(2): 83-92. DOI:10.1016/j.eja.2011.04.002.

Beatty, P. H., Anbessa, Y., Juskiw, P., Carroll, R. T., Wang. J., & Good, A. G. (2010). Nitrogen use efficiencies of spring barley grown under varying nitrogen conditions in the field and growth chamber. *Annals of Botany,* 105, 1171–1182.

Behera, U.K., & Sharma, A.R. (2014). Productivity and Water Use Efficiency of Wheat (*Triticum aestivum*) under Different Resources Conservation Techniques and Irrigation Regimes. *Cereal Research Communications*, 42 (3): 4439 – 449.

Bharti, K., Mohanty, S. R., Padmavathi, P. V. L., Rao, V. R., & Adhya, T. K. (2000). Influence of six nitrification inhibitorson methane production in a flooded alluvial soil. *Nutrient Cycling and Agroecosyst*, 58, 389–394.

Belay, A., Gebrekidan, H., & Uloro, Y. (1998). Effect of tie ridges on grain yield response of Maize (*Zea mays L.*) to application of crop residue and residual N and P on two soil types at Alemaya, Ethiopia. *South African Journal of Plant and Soil,* 15(4): 123-129, DOI: 10.1080/02571862.1998.10635130.

Berg, W.A. (1997). Residual nitrogen effects on wheat following legumes in the Southern Plains. *Journal of Plant Nutrition,* 20, 247–254.

Bingham, I., Karley, A., White, P., Thomas, W., & Russell, J. (2012). Analysis of improvements in nitrogen use efficiency associated with 75 years of spring barley breeding. *European Journal of Agronomy,* 42, 49–58.

Bolan, N. S., & Hedley, M. J. (2003). *Role of carbon, nitrogen, and sulfur cycles in soil acidification. In ''Handbook of Soil Acidity''* (Z. Rengel, Eds.), Marcek Dekker, New York. 29–52.

Bouman, B., 2007. A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agricultural Systems,* 93, 43-60.

Brady, N. C., & Weil, R. R. (2002). The Nature and Properties of Soils. *Agroforestry Systems,* 54(3): 249 – 249. DOI: 10.1023/A: 1016012810895

Bremner, J. M., & Keeney, D. R. (1965). Steam Distillation Methods for the Determination of Ammonium, Nitrate and Nitrite. *Analatica Chimica Acta*, 32, 485–495.

Brueck, H. (2008). Effects of nitrogen supply on water-use efficiency of higher plants. *Journal of Plant Nutrition and Soil Science,* 171, 210–219. https://doi.org/10.1002/jpln.200700080

Buresh, R. J., Peng, S. B., Huang, J. L., Yang, J. C., Wang, G. H., Zhong, X. H., & Zou, Y. B. (2004). Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment''. In A. R. Mosier, J. K. Syers, & J. R. Freney (Eds.)*, Rice systems in China with high nitrogen inputs*. (143–153.). Island Press, Washington, USA.

Burns D. (2004). The effects of atmospheric nitrogen deposition in the Rocky Mountains of Colorado and southwestern Wyoming, USA: A critical review. *Environmental Pollution,* 127, 257–269.

Cabrera, V.E., Jagtap, S.S., & Hildebrand. (2007). Strategies to limit (minimize) nitrogen leaching on dairy farms driven by seasonal climate forecasts. *Agricultural Ecosystem Environment*, 122, 479–489.

Cassman, K.G., Peng, S., Olk, D.C., Ladha, J.K., Reichardt, W., Dobermann, A., & Singh, U. (1998). Opportunities for increased nitrogen- use efficiency from improved resource management in irrigated rice systems. *Field Crops Research,* 56, 7-39.

Cassman, K. G., Dobermann, A., & Walters, D. T. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio: A Journal of the Human Environment,* 31 (2): 132–140.

Chen, X., Cui, Z., Fan, M., Vitousek, P., Zhao, M., Ma, W., Wang, Z., Zhang, W., Yan, X., Yang, J., Deng, X., Gao, Q., Zhang, Q., Guo, S., Ren, J., Li, S., Ye, Y., Wang, Z., Huang, J., Tang, Q., Sun, Y., Peng, X., Zhang, J., He, M., Zhu, Y., Xue, J., Wang, G., Wu, L., An, N., Wu, L., Ma, L., Zhang, W., & Zhang, F. (2014). Producing more grain with lower environmental costs. *Nature Journal,* 514, 486-489.

Chien, S.H., Teixeira, L.A., Cantarella, H., Rehm, G.W., Grant, C.A., & Gearhart, M.M. (2016). Agronomic effectiveness of granular nitrogen/phosphorus fertilizers containing elemental sulfur with and without ammonium sulfate: A Review. *Agronomy Journal,* 108, 1203.

Chepkemoi, J. (2014*).* Influence of tillage practices, cropping systems and organic inputs on soil moisture content, nutrients status and crop yield in Matuu, Yatta sub county, Kenya (Unpublished MSc Thesis). University of Nairobi, Kenya.

Chiroma, A., Alhassan, A., & Khan, B. (2008). Yield and water use efficiency of millet as affected by land configuration treatments. *Journal of Sustainable Agriculture,* 32(2), 321-333.

Ciampitti, I.A., & Vyn, T.J. (2013). Grain nitrogen source changes over time in maize: a review. *Crop Science,* 53(2)*:* 366–377. https://doi.org/10.2135/cropsci2012.07.0439.

Conacher, J., & Conacher, A. (1998). Organic farming and the environment, with particular reference to Australia: Areview. *Biological Agriculture Horticulture, 16,*145–171.

Cook, R.J. (1990). Diseases caused by root-infecting pathogens in dryland agriculture. *Advavced Soil Science Journal,* 13, 214–239.

Critchley, W. (1991). Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. *Food and Agriculture Organization of the United Nations*, 154p.

Critchley, W. (1992). Indigenous Soil and Water Conservation: Prospects for Building on Tradition. *Silsoe Research Institute*, 43p.

Danga, B., Ouma, J., Wakindiki, I., & Bar-Tal, A. (2009). Wheat rotation effects on residual soil moisture, nitrogen and wheat yield in Tropical regions. *Advances in Agronomy,* 101, 315 – 349. DO: 10.1016/S0065-2113 (08)00805-5.

Davis, R. L., Patton, J. J., Teal, R. K., Tang, Y., Humphreys, M. T., Mosali, J., Girman, J., Lawles, J. M., Moges, S. M., Malapati, A., Si, J., Zhang, H., Deng, S., Johnson, G. V., Mullen, R. W., & Raun, W. R. (2003). Nitrogen balance in the magruder plots following 109 years of continuous winter wheat. *Journalof Plant Nutrition,* 26, 1561 – 1580.

Dawson, J.C., Huggins, D.R., & Jones, S.S. (2008). Characterizing nitrogen use efficiency in natural and agricultural ecosystems to improve the performance of cereal crops in low-input and organic agricultural systems. *Field Crops Research Journal,* 107, 89-101.

Dejene, M., & Lemlem, M. (2012). Integrated Agronomic Crop Management to Improve Teff Productivity under Terminal Drought. In I.M. Rahmand and H. Hasegawa (Eds). *Water stress. Technology Open Science Journal,* 235-254.

De Koeijer, T.J., de Buck, A.J., Wossink, G.A.A., Oenna, J., Renkema, J.A., & Struik, P.C. (2003). Annual variation in weather: its implications for sustainability in the case of optimising nitrogen input in sugar beet. *European Journal of Agronomy,* 19, 251–264.

Delogu, G., Cattivelli, L., Pecchioni, N., Defalcis, D., Maggiore, T., & Stanca, A.M. (1998). Uptake and agronomic efficiency of nitrogen in winter barley and winter wheat. *European Journal of Agronomy,* 9, 11-20.

Deng, X.P., Shan, L., Zhang, H., & Turner, N.C. (2004). New directions for a diverse planet. *In: Proceeding of the 4th International Crop Science Congress,* Sept., 26th –1st Oct., 2004, Brisbane, Australia.

Dhakal, Y., Meena, R.S., & Kumar, S. (2016). Effect of INM on nodulation, yield, quality and available nutrient status in soil after harvest of green gram. *Legume Research Journal,* 39(4): 590–594.

Dobermann, A. (2007). Nutrient use efficiency—measurement and management. In: Krauss, A., Isherwood, K., Heffer, P. (Eds.), *Fertilizer Best Management Practices: General Principles, Strategy for Their Adoption and Voluntary Initiatives Versus Regulations*. International Fertilizer Industry Association, Paris, France, pp. 1–28. Online @ https://www.fertilizer.org//images/Library_Downloads/2007_IFA_FBMP%20Workshop_Brussels .

Dobermann, A., & Cassman, K. G. (2004). Environmental dimensions of fertilizer nitrogen: What can be done to increase nitrogen use efficiency and ensure global food security? *In Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment''* [A. R. Mosier, J. K. Syers, and J. R. Freney, Eds. Paris, France], 261–278.

Doorenbos, J., Pruit, W.O., Aboukhaled, A., Damagnez, J., Dastane, N.G., Berg, C.V.N., Rijtema, P.E., Ashford, O.M., & Frere, M. (1992). Crop Water Requirement. *FAO Irrigation and Drainage paper,* Rome, 1 – 156.

Duan, Y., Shi, X., Li, S., Sun, X., & He, X. (2014). Nitrogen Use Efficiency as Affected by Phosphorus and Potassium in Long-Term Rice and Wheat Experiments. *Journal of Integrative Agriculture,* 13(3): 588–596. DOI: 10.1016/S2095-3119(13)60716-9.

Dunn, J., & Grider, M.H. (2021). Physiology, Adenosine Triphosphate. [Updated 2021 Feb 27]. In: *StatPearls [Internet]*. Treasure Island (FL): StatPearls Publishing; 2021 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK553175/

Duxbury, J.M., Smith, M.S., & Doran, J.M. (1989). Soil Organic Matter as a Source and a Sink of Plant Nutrients. In: *Dynamics of Soil Organic Matter in Tropical Ecosystems; University of Hawaii: Honolulu, HI, USA,* 2, 33–67.

Edmonds, D.E., Abreu, S.L., West, A., Caasi, D.R., Conley, T.O., Daft, M.C., Desta, B., England, B.B., Farris, C.D., Nobles, T.J., Patel, N.K., Rounds, E.W., Sanders, B.H., Shawaqfeh, S.S., Lakmini., Lokuralalage., Manandhar, R., & Raun, W.R. (2009). Cereal Nitrogen Use Efficiency in Sub Saharan Africa. *Journal of Plant Nutrition,* 32(12) DOI: 10.1080/01904160903308184.

Eid, E.M., Alrumman, S.A., El-Bebany, A.F., Fawy, K.F., Taher, M.A., Hesham, A.E., Gamal A. El-Shaboury, G.A., Mohamed, T., & Ahmed, M.T. (2018). The evaluation of sewage sludge application as a fertilizer for broad bean (Faba sativa Bernh.) crops. *Food and Energy Security Journal,* 1-13, 2018; 7:e00142. DOI: 10.1002/fes3.142.

Espinoza, S., Ovalle, C., Zagal, E., Iván, M., & Alejandro, D. P. (2015). Contribution of legumes to the availability of soil nitrogen and its uptake by wheat in Mediterranean environments of central Chile. *Chilean Journal of Agricultural Research*, *75* (1): 111-121. https://dx.doi.org/10.4067/S0718-58392015000100016.

Espinoza, S., Ovalle, C., Zagal, E., & De Pozo, A. (2012). Contribution of legumes to wheat productivity in Mediterranean environments of Central Chile. *Field Crops Research,* 133,150–159. DOI: 10.1016/j.fcr.2012.03.006.

Evans, J., Fettell, N.A., Coventry, D.R., Connor, G.E., Walsgott, D.N., Mahoney, J., & Armstrong, E.L. (1991). Wheat responses after temperate crop legumes in South-Eastern Australia. *Australian Journal of Agricultural Research,* 42, 31–43.

Fageria, N. K., Baligar, V. C. & Li, Y. C. (2008). The Role of Nutrient Efficient Plants in Improving Crop Yields in the Twenty First Century. *Journal of Plant Nutrition,* 31 (6): 1121 - 1157. DOI: 10.1080/01904160802116068.

Fageria, N. K. (2007). Yield physiology of rice. *Journal of Plant Nutrition*, 30 (6), 843–879.

Fageria, N.K., & Baligar, V. (2005). Enhancing Nitrogen Use Efficiency in Crop Plants. *Advances in Agronomy,* 88, 97 – 185. DO - 10.1016/S0065-2113(05)88004-6.

Fageria, N. K. (2002). Soil quality vs. environmentally based agriculture. *Communications in Soil Science ad Plant Analysis*., 33**,** 2301–2329.

Fageria, N. K., & Barbosa, M. P. (2001). Nitrogen use efficiency in lowland rice genotypes. *Soil Science and Plant Analysis*, 32, 2079 – 2089.

FAO. **(**2016). FAOSTAT Database. Available at http://faostat3.fao.org/browse/R/RP/E Accessed July 2016. *Rome, Food and Agriculture Organization of the United Nations (FAO).*

FAO**. (**2014). Area equipped for irrigation. Infographic. AQUASTAT: FAO's information system on water and agriculture. *Food and Agriculture Organization of the United Nations (FAO),* Rome (available at: http://www.fao.org/nr/water/aquastat/infographics/ Irrigation_eng.pdf).

FAO. (2009). How to Feed the World in 2050 - High-Level Expert Forum Nutrient limitation and soil development: *Experimental test of a biogeochemical theory*. Available at: *http://www.fao.org/wsfs/forum2050/wsfs-forum/en/.*

Feddes, R., & Raats, P. (2004). Parameterizing the soil–water–plant root system, in *Unsaturated-zone Modeling: Progress, Challenges, and Applications. Wageningen UR Frontis Series,* (Feddes R. A., de Rooij G. H., van Dam J. C., editors). (Dordrecht: kluwer academic publishers), 6, 95–141.

Feil, B. (1992). Breeding progress in small grain cereals-a comparison of old and modern cultivars. *Plant Breeding Journal,* 108, 1-11.

Fentaw, B., Alamerew E., & Ali, S. (2002). Traditional rainwater harvesting systems for food production: the case of Kobo Wereda, Northern Ethiopia. In: *Rainwater Harvesting for Improved Food Security: Promising Technologies in the Greater Horn of Africa*. Greater Horn of Africa Rainwater Partnership (GHARP) and Kenya Rainwater Association (KRA), Nairobi, Kenya, Ngugi, S.N. eds.), 123 – 131.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D. and Zaks, D.P.M. (2011). Solutions for a cultivated planet. *Nature Journal,* 478, 337-342.

Fowler, D., Coyle, M., Skiba, U., Sutton, M.A., Cape, J.N., Reis, S., Sheppard, L.J., Jenkins, A., Grizzetti, B., Galloway, J.N., Vitousek, P., Leach, A., Bouwman, A.F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M. and Voss, M. (2013). The global nitrogen cycle in the twenty-first century. *Philosophical Transactions Royal Society and Biological Sciences,* 368, 1 - 13. DOI: 10.1098/rstb.2013.0164.

French, R.J., & Schultz, J.E. (1984). Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research,* 35, 765–775. DOI: 10.1071/AR9840765.

Fu, Q., Wang, Q., Shen, X., & Fan, J. (2014). Optimizing water and nitrogen inputs for winter wheat cropping system on the Loess Plateau, China. *Journal of Arid Land,* 6(2): 230-242.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., & Sutton, M.A. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Journal of Science,* 320, 889-892.

Gan, Y.T., Miller, P.R., McConkey, B.G., Zentner, R.P., Stevenson, F.C., & McDonald, C.L. (2003). Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid Northern Great Plains. *Agronomy Journal,* 95, 245–252.

Garnett, T., Conn, V., Plett, D., Conn, S., Zanghellini, J., Mackenzie, N., Enju, A., Francis, K., Holtham, L., Roessner, U., Boughton, B., Bacic, A., Shirley, N., Rafalski, A., Dhugga,

K., Tester, M., & Kaiser, B.N. (2013). The response of the maize nitrate transport system to nitrogen demand and supply across the lifecycle. *New Phytologist,* 198, 82–94. DOI: 10.1111/nph.12166.

Geng, Y., Cao, G., Wang, L., & Wang, S. (2019). Effects of equal chemical fertilizer substitutions with organic manure on yield, dry matter, and nitrogen uptake of spring maize and soil nitrogen distribution. *PLoSONE,* 14 (7): e0219512. https://doi.org/ DOI: 0.1371/journal.pone.0219512

Genstat 5 Committee. (1993). *Genstat 5 release 3 Reference manual*. Oxford University Press Oxford, UK.

Gewin, V. (2010). Food: an underground revolution. *Nature* 466, 552–553..https://doi.org/ 10.1038/466552a.

Giambalvo, D., Ruisi, P., Miceli, G. D., Frenda, A. S., & Amato, G. (2010). Nitrogen use efficiency and nitrogen fertilizer recovery of durum wheat genotypes as affected by interspecific competition. *Agronomy Journal,* 102, 707-715. http://dx.doi.org/10.2134/agronj2009.0380

Giller, K. E., Chalk, P. M., Dobermann, A., Hammond, L., Hever, P., Ladha, J. K., Maene, L., Nyamudeza, P., Ssali, H., & Freney, J. R. (2004). Emerging technologies to increase the efficiency of use of fertilizer nitrogen. In:*''Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment''* (A. R. Mosier,J. K. Syers, and J. R. Freney, Eds. Paris, France.), 35–51.

Giller, K.E. (2001). *Nitrogen Fixation in Tropical Cropping Systems*, 2nd edn. CABI Publishing division, CAB International, Wallingford.

Google. (Undated). Map showing the location of the study area in Njoro Sub-County.

Gould, J. (1999). Contributions relating to rainwater harvesting. *Contributing paper. World Commission on Dams.* New Zealand.

Graham, P.H., & Vance, C.P. (2003). Legumes: importance and constraints to greater use. *Plant Physiology,* 131, 872–877.

Green, B.W. (2015). Feed and feeding practices in Aquaculture. *Woodhead Publishing Series in Food Science, Technology and Nutrition,* 27 - 52. https://doi.org/10.1016/B978-0-08-100506-4.00002-7.

Gregory, A. S., Ritz, K., McGrath, S. P., Quinton, J. N., Goulding, K. W., Jones, R. J., Harris, J.A., Bol, R., Wallace, P., Pilgrim, E. S., & Whitmore, A. P. (2015). A review of the impacts of degradation threats on soil properties in the UK. *Soil Use and Management*, *31*(Suppl 1): 1–15. https://doi.org/10.1111/sum.12212.

Guo, Z., Zhang, Y., Zhao, J., Shi, Y., & Yu, Z. (2014). Nitrogen use by winter wheat and changes in soil nitrate nitrogen levels with supplemental irrigation based on measurement of moisture content in various soil layers. *Field Crops Research,* 164, 117-125. http://dx.doi.org/10.1016/j.fcr.2014.05.016.

Haile, D., Nigussie, D., & Ayana, A. (2012). Nitrogen use efficiency of bread wheat: Effects of nitrogen rate and time of application. *Journal of Soil Science and Plant Nutrition,* 12(3): 389-409.

Halvorson, A.D., Nielsen, D.C., & Reule, C.A. (2004). Nitrogen fertilization and rotation effects on no-till dryland wheat production. *Agronomy Journal,* 96, 1196-1201.

Han, M., Okamoto, M., Beatty, P.H., Rothstein, R.J., & Good, A.G. (2015). The genetics of nitrogen use efficiency in crop plants. *Annual Review of Genetics,* 49, 269–289. https://doi.org/10.1146/annurev-genet-112414-055037.

Hatfield, J. L., & Dold, C. (2019). Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Frontiers in Plant Science | www.frontiersin.org,* 1 - 14. *DOI*: 10.3389/fpls.2019.00103.

Hawkesford, M. J. (2012). The diversity of nitrogen use efficiency for wheat varieties and the potential for crop improvement. *Better Crops,* 96, 10-12.

Hayat, R., & S. Ali. (2010). Nitrogen fixation of legumes and yield of wheat under legumes-wheat rotation in Pothwar. *Pakistan Journal of Botany,* 42, 2317-2326.

Hirel, B., Tétu, T., Lea, P.J., & Dubois, F. (2011). Improving nitrogen use efficiency in crops for sustainable agriculture. *Sustainability,* 3, 1452–1485.https://doi.org/ 10.3390/su3091452.

Hirel, B., Le Gouis, J., Ney, B., & Gallais, A. (2007). The challenge of improving nitrogen use efficiency in crop plants: Towards a more central role for genetic variability and quantitative genetics within integrated approaches. *Journal of Experimental Botany,* 58**,** 2369–87.

Hoekstra, A.Y., & Wiedmann, T.O. (2014). Humanity's unsustainable environmental footprint. *Science,* 344, 1114 - 1117.

Hoekstra, A.Y., & Mekonnen, M.M. (2012). The water footprint of humanity. *Proceedings of the National Academy of Sciences of the United States of America,* 109, 3232-3237.

Howell, T.A., Schneider, A.D., & Dusek, D.A. (2002). Effects of furrow diking on corn response to limited and full sprinkler irrigation. *Soil Science Society of America Journal,* 66, 222–227.

Hoque, T.S, Akter, F., & Islam, M.R. (2016). Residual effects of different green manures on the growth and yield of wheat. *Asian J. Med. Biol. Res.,* 2(4): 624 – 630. DOI: .3329/ajmbr.v2i4.31006.

Hulugalle, N. R. (1990). Alleviation of soil constraints to crop growth in the upland and associated soil groups of the West African Sudan savannah by tie ridges. *Soil and Tillage Research,* 18 (2–3): 231-247.

Hunt, J., & Kirkegaard, J. (2012). A guide to consistent and meaningful benchmarking of yield and reporting of water-use efficiency. *Sustainable Agriculture, CSIRO. www.csiro.au.*

Hussain, I., Ali, A., Ahmed, A., Nasrullah, H., Khokhar, B.D., Iqbal, S., Aulakh, A.M., Khan, A.U., Akhter, J., & Ahmed, G. (2018). Impact of Ridge-Furrow Planting in Pakistan: Empirical Evidence from the Farmers Field. *International Journal of Agronomy,* 1 – 8. Article ID 3798037, 8 pages https://doi.org/10.1155/2018/3798037.

Hutchinson, C., Simonne, E., Solano, P., Meldrum, J., & Livingston-Way, P. (2003). Testing of controlled release fertilizer programs for seep irrigated Irish potato production. *Journal of Plant Nutrition,* 26, 1709–1723.

Igrejas G., & Branlard G. (2020). The Importance of Wheat. In: *Igrejas G., Ikeda T., Guzmán C. (eds) Wheat Quality For Improving Processing And Human Health*. Springer, Cham. https://doi.org/10.1007/978-3-030-34163-3_1.

IMKO. (1996). *Theoretical aspects on measuring moisture using TRIME®.* IMKO Micromodultechnik GmbH, Ettlingen, Germany.

IPCC. (2007). *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on*

Climate Change In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E.Hanson, Eds., Cambridge University Press, Cambridge, UK, 976p.

Jackson, M.L. (1973). Soil Chemical Analysis. Prentice Hall of India Pvt. Ltd., New Delhi, 498.

Jaetzold, R., Schmidt, H., Hornetz, B., & Shisanya, C. (2011). *Farm Management Handbook of Kenya.* Vol. II. Natural Conditions and Farm Management Information. 2nd Edition, Part B, Central Kenya Subpart B1b Northern Rift Valley Province, Ministry of Agriculture, Nairobi.

Järvan, M., Vettik, R., & Tamm, K. (2017). The importance and profitability of farmyard manure application to an organically managed crop rotation. *Zemdirbyste-Agriculture,* 104(4): 321–328. DOI 10.13080/z-a.2017.104.041.

Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., Alves, B.J., & Morrison, M.J. (2012). Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries: A review. *Agronomy for Sustainable Development,* 32 (2): 329–364.

Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. (2010). Faba bean in cropping systems. *Field Crops Research,* 115 (3): 203-216. http://dx.doi.org/10.1016/j.fcr.2009.10.008.

Ju, X.T., Xing, G.X., Chen, X.P., Zhang, S.L., Zhang, L.J., Liu, X.J., Cui, Z.L., Yin, B., Christie, P., Zhu, Z.L., & Zhang, F.S. (2009). Reducing environmental risk by improving N management in intensive Chinese agricultural systems. *Proceedings of the National Academy of Sciences of the United States of America,* 106, 3041-3046.

Kamwaga, J., Macharia, G., Boyd, L., Chiurugwi, T., Midgley, I., Canales, C., Marcheselli, M., & Maina, I. (2016). *Kenya Wheat Production Handbook*. Kenya Agricultural and Livestock Research Organization, Nairobi, Kenya.

Kang, Y., Khan, S., & Ma, X. (2009). Climate Change impacts on crop yield, crop water productivity and food security: A review: *Progress in Natural Science,* 19, 1665 – 1674.

Kang, S.Z., Zhang, L., Liang, Y.L., Hu, X.T., Cai, H.J., & Gu, B.J. (2002). Effects of limited irrigation on yield andwater use efficiency of winter wheat in the Loess Plateau of China. *Agricultural Water Management,* 55, 203-216.

Khan, S., Anwar, S., Shaobo, Y., Gao, Z., Sun, M., Ashraf, M.Y, Ren, A., & Yang, Z. (2020). Soil water consumption, water use efficiency and winter wheat production in response to nitrogen fertilizer and tillage. *Peer Journal,* 8:*e8892.* https://doi.org/10.7717/peerj.8892.

Khan, D.F., Peoples, M.B., Schwenke, G.D., Felton, W.L., Chen, D., & Herridge, D.F. (2003). Effects of below-ground nitrogen on N balances of field-grown fababean, chickpea and barley. *Australian Journal of Agricultural Research,* 54, 333–340.

Khan, D.F., Peoples, M.B., Chalk, P.M., & Herridge, D.F. (2002). Quantifying below-ground nitrogen of legumes. 2. Comparison of ^{15}N and non isotopic methods. *Plant Soil,* 239, 277–289.

Karuku, G.N. (2018). Soil and Water Conservation Measures and Challenges in Kenya: a review. *Current Investigations in Agriculture and Current Research*, 259-279. DOI:10.32474/CIACR.2018.02.000148.

Karrar, A.B., Mohamed, H.I., Elramlwai, H.R., Saeed, A.B., & Idris, A.E. (2012). Effects of some in-situ water harvesting techniques on soil moisture and sorghum (*Sorghum bicolor* (L.) Moench) production in Northern Gedaref State. *Global Journal of Plant Ecophysiology,* 2(1): 54-66.

Kaul, H.P. (2004). Pre-crop effects of grain legumes and linseed on soil mineral N and productivity of subsequent winter rape and winter wheat crops. *Bodenkultur,* 55, 95 – 102.

Kibblewhite, M.G., Ritz, K., & Swift, M.J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society and Biological Sciences*, 363(1492): 685-701. DOI:10.1098/rstb.2007.2178.

Kichey, T., Hirel, B., Heumez, E., Dubois, F., & Le Gouis, J. (2007). In winter wheat (*Triticum aestivum* L.), post-anthesis nitrogen uptake and remobilization to the grain correlates with agronomic traits and nitrogen physiological markers. *Field Crops Research,* 102, 22-32. http://dx.doi.org/10.1016/j.fcr.2007.01.002.

Kirkegaard, J., & Hunt, J. (2013). Short and long-term focus needed to lift WUE. Ground Cover Supplement-Water Use Efficiency, edited by J Paterson. *Grains Research and Development Corporation,* Canberra, Australia. ISBN 1039-6217.

Kirkegaard, J.A., Christen, O., Krupinsky, J., & Layzell, D.B. (2008). Break crop benefits in temperate wheat production. *Field Crops Research,* 107, 185-195.

Kopke, U. (2004). Rotation for Organic Agriculture: Its aims and implementation. *International Sympossium on Organic Agriculture, Research Institute of Organic Agricullture,* Dankook University, Uljin/Korea, August 20th – 21st, 2004.

Kouyaté, Z., Diallo, D., N'Diaye, K., & Ayemou, A. (2012). Influence of crop management systems on soil properties and sorghum yields in the Sahelian zone of Mali. *African Journal of Agricultural Research,* 7(37): 5217-5223.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters,* 9, 105011 (9pp).

Lebel, S., Fleskens, L., Forster, P.M., Jackson, L.S., & Lorenz, S. (2015). Evaluation of In Situ Rainwater Harvesting as an Adaptation Strategy to Climate Change for Maize Production in Rainfed Africa. *Water Resource Management,* 29, 4803–4816. DOI: 10.1007/s11269-015-1091-y.

Lee, H.J., Lee, S.H., & Chung, J.H. (2004). Variation of nitrogen use efficiency and its relationships with growth characteristics in Korean rice cultivars. In: *Proceedings of the 4th International Crop Science Congress*, Brisbane, Australia, 26th Sept –1st Oct 2004, ISBN 1 920842 20 9.

Le-Gouis, J., Beghin, D., Heumez, E., & Pluchard, P. (2000). Genetic differences for nitrogen uptake and nitrogen utilization efficiencies in winter wheat. *European Journal of Agronomy,* 12, 163–173.

Lian, Y., Meng, X., & Yang, Z. (2017). Strategies for reducing the fertilizer application rate in the ridge and furrow rainfall harvesting system in semiarid regions. *Scientific Reports,* 7(1): 2644. https://doi.org/10.1038/s41598-017-02731-y.

Limon-Ortega, A., Sayre, K.D., & Francis, C.A. (2000). Wheat nitrogen use efficiency in a bed planting system in Northwest Mexico. *Agronomy Journal,* 92(2): 303-308.

Liu, X., Li, R., Chang, X., & Jing, R. (2013). Mapping QTLs for seedling root traits in a double haploid wheat population under different water regimes. *Euphytica,* 189,51–66.

Loewy, T. (1987). Legume – Wheat rotation and Nitrogen fertilization of soil. *Soil Science Journal,* 5, 57-64.

López-Bellido, R.J., & López-Bellido, L. (2001). Efficiency of nitrogen in wheat under Mediterranean condition: effect of tillage, crop rotation and N fertilization. *Field Crop Research,* 71(1): 31-64.

López-Bellido, L., Fuentes, M., Castillo, J.E., López -Garrido, F.J., & Fernandez, E.J. (1996). Long-term tillage, crop rotation and nitrogen fertilizer effects on wheat yield under rainfed Mediterranean conditions. *Agronomy Journal,* 88, 783-791.

Ma, C.H., & Kalb, T. (2006). Development of starter solution technology as a balanced fertilization practice in vegetable production. In: F. Tei and M. Guducci (eds) *Proceedings of the International Symposium Towards Ecologically Sound Fertilization Strategies for Field Vegetable Production*, Held in Perugia, Italy, June. 2004. *Acta Hortic*, 700 (27): 167–172.

Ma, L., Wang, F.H., Zhang, W.F., Ma, W.Q., Velthof, G., Qin, W., Oenema, O., & Zhang, F.S. (2013). Environmental Assessment of Management Options for Nutrient Flows in the Food Chain in China. *Environmental Science and Technology,* 47, 7260-7268.

Mahal, N.K., Osterholz, W.R., Miguez, F.E., Poffenbarger, H.J., Sawyer, J.E., Olk, D.C., Archontoulis, S.V., & Castellano, M.J. (2019). Nitrogen Fertilizer Suppresses Mineralization of Soil Organic Matter in Maize Agroecosystems. *Frontiers in Ecology and Evolution*, 7, 59. DOI: 10.3389/fevo.2019.00059.

Majumdar, K., Jat, M.L., Pampolino, M., Dutta, S., & Kumar, A. (2013). Nutrient management in wheat: current scenario, improved strategies and future research needs in India. *Journal of Wheat Research,* 4, 1-10.

Malagoli, P., Laine, P., Rossato, L., & Ourry, A. (2005). Dynamics of nitrogen uptake and mobilization in field-grown winter oilseed rape (*Brassica napus*) from stem extension to harvest—I. *Global N flows between vegetative and reproductive tissues in relation to leaf fall and their residual N. Annals of Botany,* 95(5): 853–861. https://doi.org/10.1093/aob/mci091

Manna, M.C., Swarup, A., Wanjari, R.H., Mishra, B., & Shahi, D.K. (2007). Long-term fertilization, manure and liming effects on soil organic matter and crop yields. *Soil and Tillage Research,* 94 (2): 397-409. https://doi.org/10.1016/j.still.2006.08.013.

Mansour, E., Merwad, A.M.A., Yasin, M.A.T., Abdul – Hamid, M.I.E., El – Sobky, E.E.A., & Oraby, H.F. (2017). Nitrogen use efficiency in spring wheat: genotypic variation and grain yield response under sandy soil conditions. *The Journal of Agricultural Science,* 155 (9): 1407-1423. DOI:10.1017/S0021859617000600.

Mary, B., & Recous, S. (1994). Measurement of nitrogen mineralization and immobilization fluxes in soil as a means of predicting net mineralization. *European Journal of Agronomy*, 3 (4): 291–300.

Masclaux-Daubresse, C., Daniel, V. F., Dechorgnat, J., Chardon, F., Gaufichon, L., & Suzuki, A. (2010). Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. *Annals of botany,* 105(7): 1141-1157.

Masebo, A.M., Tadesse, T., & Utta, H.Z. (2008). Evaluating the Effects of In-situ Rainwater Harvesting Techniques on Soil Moisture Conservation and Grain Yield of Maize (*Zea mays* L.) in Fedis District, Eastern Hararghe, Ethiopia. September 2018. *Turkish Journal of Agriculture - Food Science and Technology,* 6(9):1129. DOI:10.24925/turjaf.v6i9.1129-1133.1839

McBratney, A.B., Minasny, B., & Whelan, B.M. (2003). Obtaining 'useful' high-resolution soil data from proximally-sensed electrical conductivity (PSEC/R) surveys. In: Stafford J.V. (ed.), *Precision agriculture '05*. Wageningen Academic Publishers, Wageningen, The Netherlands and Sweden, 503-511.

McCallum, M.H., Kirkegaard, J.A., Green, T., Cresswell, H.P., Davies, S.L., & Angus, J.F. (2004). Improved subsoil macro-porosity following perennial pastures. *Australian Journal of Experimental Agriculture,* 44, 299-307.

McNeill, A.M., & Fillery, I.R.P. (2008). Field measurement of lupine below ground nitrogen accumulation and recovery in the subsequent cereal-soil system in a semi-arid Mediterranean-type climate. *Plant and Soil,* 302, 297–316.

Meena, B.L., Fagodiya, R.K., Kaledhonkar, M., Sharma, P., Meena, R.S., Mitran, T., & Kumar, S. (2018). Legume Green Manuring: An Option for Soil Sustainability. R.S. Meena *et al.* (eds.), *Legumes for Soil Health and Sustainable Management,* 387-408. *Springer Nature Singapore,* 2018. DOI: 10.1007/978-981-13-0253-4_12.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis,* 15 (12), 1409 – 1416. DOI: 10.1080/00103628409367568

Mercinkeviciene, A., Pupaliene. R., Bogus, V., & Balnyte, S. (2008). Influence of Crop Rotation and Catch crop for green manure on nitrogen balance in organic farming. *Zemes Ukio Mokslai.* 15(4):16-20.

Miller, P.R., Bekkerman, A., Jones, C.A., Burgess, M.H. Holmes, J.A., & Engel, R.E. (2015). Pea in rotation with wheat reduced uncertainty of economic returns in southwest Montana. *Agronomy Journal,* 107, 541– 550. DOI: https://doi.org/10.2134/agronj14.0185,

Miriti, J., Esilaba, A. O., Bationo, A., Cheruiyot, H., Kihumba, J., & Thuranira, E. (2007). Tie ridging and integrated nutrient management options for sustainable crop production in semi-arid eastern Kenya. In *A. Bationo, B. Waswa, J. Kihara and J. Kimetu, (eds.) Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities,* 435 - 442. Springer, Netherlands.

MoALF. (2016)**.** *Climate Risk Profile for Nakuru. Kenya County Climate Risk Profile Series.* The Kenya Ministry of Agriculture, Livestock and Fisheries (MoALF), Nairobi, Kenya

Molden, D., Frenken, K., & Barker, R. (2007). Trends in water and agricultural development. In: *Water for food, water for life: a comprehensive assessment of water management in agriculture, (Eds)*. D. Molden, 57–89. London, UK: Earthscan; and Colombo, Sri Lanka: International Water Management Institute.

Molden, D. (2007). Water for food, Water for life: A Comprehensive Assessment of Water Management in Agriculture. *Earthscan, 645p.* Internal Water Management Institute.

Moll, R.H., Kamprath, E.J., & Jackson, W.A. (1982). Analysis and interpretation of factors which contribute to efficiency of nitrogen utilization. *Agronomy Journal*, 74, 562–564. DOI:10.2134/agronj1982.00021962007400030037x.

Moorhead, D. L., & Sinsabaugh, R. L. (2006). A theoretical model of litter decay and microbial interaction. *Ecological Monograph,* 76, 151–174. DOI: 10.1890/0012-9615(2006)076.

Mosier, A. R., Bleken, M. A., Chaiwanakupt, P., Ellis, E. C., Freney, J. R., Howarth, R. B., Matson, P. A., Minami, K., Naylor, R., Weeks, K. N., & Zhu, Z. L. (2001). Policy implications of Human accelerated nitrogen cycling. *Biogeochemicals,* 52**,** 281–320.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., & Foley, J.A. (2012). Closing yield gaps through nutrient and water anagement. *Nature,* 490(7419): 254-257. DOI: 10.1038/nature11420.

Mugwe, J., Mugendi, D., Kungu, J., & Mucheru – Muna. (2007). Effect of plant Biomass, Manure and inorganic fertilizeron maize yield in the Central Highlands of Kenya. *African Crop Science Journal,* 15(3): 111-126.

Muhammad, A., Khan, H., Anjum, M.M., Ali, N., & Hamid, M. (2017). Effect of farm yard manure and phosphorous levels on yield and yield components of wheat. *International Journal of Environmental Science and Natural Resources,* 2(4): 0133 0137. DOI: 10.19080/IJESNR.2017.02.555595.

Muramoto, J., Smith, R.F., Shennan, C., Klonsky, K.M., Leap, J., & Ruiz, M.S. (2011). Nitrogen contribution of legume/cereal mixed cover crops and organic fertilizers to an organic broccoli crop. *HortScience,* 46, 1154– 1162.

Muthuri, J.K. (2013). Effect of different soil fertility amendments on the nodulation and yield of two soyabean varities. *Unpublished MSc thesis.* Kenyatta University, Kenya.

Mutunga, K. (2001). Water conservation, harvesting and management (WCHM) – Kenyan experience. In: *Proceedings of the 10th International Soil Conservation Organization Conference* held on 24 - 29th, May, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, D.E. Stott, R.H. Mohtar and G.C. Steinhardt, eds), 1139-1143.

Muurinen, S., Kleemola, J., & Peltonen – Sainio, P. (2007). Accumulation and Translocation of Nitrogen in Spring Cereal Cultivars Differing in Nitrogen Use Efficiency. *Agronomy Journal,* 9(2): 441 -449. https://doi.org/10.2134/agronj2006.0107.

Mwende, G. (2019). *Soil Moisture Conservation, Cropping Systems and Soil Fertility Effects on Soil and Maize Performance in Machakos County, (Unpublished Doctoral Dissertation)*, Kenyatta University, Nairobi, Kenya.

Nacry, P., Bouguyon, E., & Gojon, A. (2013). Nitrogen acquisition by roots: physiological and developmental mechanisms ensuring plant adaptation to a fluctuating resource. *Plant and Soil,* 370, 1-29. DOI 10.1007/s11104-013-1645-9.

N'Dayegamiye, A., & Tran, T.S. (2001). Effects of green manure on soil organic matter and wheat yield and N nutrition. *Canadian Journal of Soil Science,* 81, 371 - 382.

Nehra, A.S., & Hooda, I.S. (2002). Influence of integrated use of organic manures and inorganic fertilizers on wheat yields and soil properties. *Research on Crops,* 3(1):11-16.

Nieder, R., & Benbi, D. (2008). Carbon and Nitrogen in the Terrestrial Environment. *Springer.* Dordrecht, South Holland, Netherlands.

Nin, Y.; Diao, P., Wang, Q., Zhang, Q., Zhao, Z., & Li, Z. (2016). On-Farm-Produced Organic Amendments on Maintaining and Enhancing Soil Fertility and Nitrogen Availability in

Organic or Low Input Agriculture. *Organic Fertilizer*, SN - 978-953-51-2449-8. DOI:10.5772/62338.

NPBRC, Njoro Meteorological station No.9035021. (1999). Rainfall data, NPBRC Centre, Njoro, Kenya

Okalebo, J.R., Gathua, K.W. and Woomer, P.L. (2002). *Laboratory Methods of Soils and Plant Analysis*. TSBF-CIAT and SACRED Africa, Nairobi, Kenya. 79p.

Olesen, J. E., Sørensen, P., Thomsen, I. K., Eriksen, J., Thomsen, A. G., & Berntsen, J. (2004). Integrated nitrogen input systems in Denmark. In *''Agriculture and the Nitrogen Cycle: Assessing the Impacts of Fertilizer Use on Food Production and the Environment''*(A. R.Mosier, J. K. Syers, and J. R. Freney, Eds. Paris, France.), 129–140.

Omara, P., Aula, L., & Raun, W.R. (2019). Nitrogen Uptake Eficiency and Total Soil Nitrogen accumulation in Long - Term Beef Manure and Inorganic Fertilizer application. *International Journal of Agronomy,* 1- 6. doi.org/10.1155/2019/9594369.

Osborne, C.A., Peoples, M.B., & Janssen, P.H. (2010). Detection of a reproducible, single-member shift in soil bacterial communities exposed to low levels of hydrogen. *Applied and Environmental Microbiology,* 76*,* 1471-1479.

Pacey, A., & Cullis, A. (1999). Rain water harvesting. The collection of Rainfall and Runoff inthe Rural areas. Technical Center for Agricultural and Rural cooperation (ACP – EEC Lome Convention). 216p.

Palta, J.A., Fillery, I.R., & Rebetzke, G.J. (2007). Restricted-tillering wheat does not lead to greater investment in roots and early nitrogen uptake. *Field Crops Reserach,* 104, 52–59. DOI:10.1016/j.fcr.2007.03.015.

Parkinson, J.A., & Allen, S.E. (1975). A wet digestion procedure suitable for the determination of nitrogen and mineral nutrients in biological material, *Communications in Soil Science and Plant Analysis*, 6, 1-11.

Pask, A.J.D., Pietragalla, J., Mullan, D.M., & Reynolds, M.P. (2012). Physiological Breeding II: A Field Guide to Wheat Phenotyping. *CIMMYT press,* DF, Mexico.

Patel, B.N., Solanki, M.P., Patel, S.R., & Desai, J.R. (2011). Effect of bio-fertilizers growth, physiological parameters, yield and quality of brinjal cv. Surti Ravaiya. *Indian Journal of Horticulture.* 68(3): 370-374.

Patel, H.K., Sadhu, A.C., Lakum, Y.C., & Suthar, J.V. (2014). Response of integrated nutrient management on wheat (*Triticum aestivum* L.) and its residual effect on succeeding crop. *International Journal of Agricultural Science and Veterinary Medicine,* 2 (4):48 -52.

Pathak, P., Sahrawat, K., Rego, T.J., & Wani, S. (2005). Measurable Biophysical Indicators for Impact Assessment: Changes in Soil Quality. In: Natural Resource Management in Agriculture (eds. B. Shiferaw, H.A. Freeman and S.M. Swintori). *CAB International Publishing*.

Peoples, M.B., Brockwell, J., Herridge, D.F., Rochester, I.J., Alves, B.J.R., Urquiaga, S., Boddey, R.M., Dakora, F.D., Bhattarai, S., Maskey, S.L., Sampet, C., Rerkasem, B., Khan, D.F., Hauggaard, N.H., & Jensen, E.S. (2009). The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis,* 48, 1–17.

Phogat, V., Skewes, M.A., Cox, J.W., Alam, J., Grigson, G., & Šimůnek, J. (2013). Evaluation of water movement and nitrate dynamics in a lysimeter planted with an orange tree. *Agricultural Water Management,* 127, 74-84.

Pierce, F.J., & Rice, C.W. (1988). Crop rotation and its impact on efficiency of water and nitrogen use. *In: Hargrove (Ed), Cropping strategies for Efficient Use of Water and Nitrogen,* 15, 101-113. ASA, Special Publication, Wisconsin..

Plett, D.C., Ranathuge, K., Melino, V.J., Kuya, N., Uga, Y., & Kronzucker, M.J. (2020). The intersection of nitrogen nutrition and water use in plants: new path towards improved crop productivity. *Journal of Experimental Botany,* 1- 17. DOI: 10.1093/jxb/eraa049.

Rahimizadeh, M., Kashani, A., Zare-Feizabach, A., Koocheki, A.R., & Nassiri-Mahallati M. (2010). Nitrogen use efficiency of wheat as affected by preceding crop, application rate of nitrogen and crop residues. *Australian Journal of Crop Science,* 4 (5): 363 – 368.

Rahman, M. A., Sarker, A. Z., Amin, M. F., Jahan, H. S., & Akhter, M. M. (2011). Yield response and nitrogen use efficiency of wheat under different doses and split application of nitrogen fertilizer. *Bangladesh Journal of Agricultural Research,* 36, 231-240. http://dx.doi.org/ 0.3329/bjar.v36i2.9249.

Randall, G. W., Vetsch, J. A., & HuVman, J. R. (2003). Corn production on a subsurface drained Mollisol as aVected by time of nitrogen application and nitrapyrin. *Agronomy Journal,* 95, 1213–1219.

Raun, W.R., & Johnson, G.V. (1999). Improving nitrogen use efficiency for cereal production. *Agronomy Journal,* 91, 357 - 363.

Raun, W.R., Johnson, G.V., Phillips, S.B., & Westerman, R.L. (1998). Effect of long-term N fertilization on soil organic C and total N in continuous wheat under conventional tillage in Oklahoma. *Soil Tillage Research,* 47, 323–330.

Ray, D.K., Mueller, N.D., West, P.C., & Foley, J.A. (2013). Yield Trends Are Insufficient to Double Global Crop Production by 2050. *Plos One 8*.

Rehim, A., Khan, M., Imran, M., Bashir, M. A., Ul-Allah, S., Khan, M. N., & Hussain, M. (2020). Integrated use of farm manure and synthetic nitrogen fertilizer improves nitrogen use efficiency, yield and grain quality in wheat. *Italian Journal of Agronomy*, 15(1): 29-34. https://doi.org/10.4081/ija.2020.1360.

Ren, X., Chen, X., Cai, T., Wei, T., Wu, Y., Ali, S., Zhand, P., & Jia, Z. (2017). Effects of Ridge-Furrow System Combined with Different Degradable Mulching Materials on Soil Water Conservation and Crop Production in Semi-Humid Areas of China. *Front Plant Science,* 8, 1877.

Rochester, I.J., Peoples, M.B., Hulugalle, N.R., Gault, R.R., & Constable, G.A. (2001). Using legumes to enhance nitrogen fertility and improve soil conditions in cotton cropping systems. *Field Crops Research,* 70, 27-41.

Rockström, J., Karlberg, L., & Wani, S.P. (2010). Managing water in rainfed agriculture – The need for a paradigm shift. *Agricultural Water Management,* 97, 543–550.

Rodgers, C.O., & Barneix, A. J. (1988). Cultivar differences in the rate of nitrate uptake by intact wheat plants as related to growth rate. *Physiologia Plantarum,* 72, 121-126.

Ruffel, S., Krouk, G., Ristova, D., Shasha, D., Birnbaum, K.D., & Coruzzi, G.M. (2011). Nitrogen economics of root foraging: transitive closure of the nitrate-cytokinin relay and distinct systemic signaling for N supply vs. demand. *Proceedings of the Nationall Academy of Science, USA,* 108, 18524–18529.

Rumesh, R., Yadav, R., Kumar, A., & Mandal, S.N. (2019). Contributing traits for nitrogen use efficiency in selected wheat genotypes and corollary between screening methodologies. *Acta Agriculturae Scandinavica, Section B. Soil and Plant Science,* 69(7): 588-595. DOI: 10.1080/09064710.2019.1623302.

Sadras, V. O., & Lemaire, G. (2014). Quantifying crop nitrogen status for comparisons of agronomic practices and genotypes. *Field Crops Research,* 164, 54–64.

Sadras, V. O., & McDonald, G. (2012). Water use efficiency of grain crops in Australia: Principles, benchmarks and management. *Australian Government, GRDC and University of Adelaide,* Australia, 1 - 27.

Sadras, V.O., & Angus, J. (2006). Benchmarking water-use efficiency of rainfed wheat in dry environments. *Australian Journal of Agricultural Research,* 57, 847 - 856.

Sadras, V.O., Grassini, P., & Steduto, P. (2014). Status of Water use efficiency of main crops. SOLAW Background Thematic Report- TR07. *Land and Water Division,* FAO publication, Rome, Italy.

Sadras, V.O., & Roget, D.K. (2004). Production and environmental aspects of cropping intensification in a semiarid environment of South Eastern Australia. *Agronomy Journal,* 96, 236–246.

Sadras, V.O. (2002). Interaction between rainfall and nitrogen fertilization of wheat in environments prone to terminal drought: economic and environmental risk analysis. *Field Crops Res.* 77, 201–215.

Sha, F. (2019). Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments. *Sustainability,* 11 (5): 1485. DOI:10.3390/su11051485.

Sanginga, N., & Woomer, P.L. (2009). Integrated Soil Fertility Management in Africa: Principles, Practices and development process. *Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture. Nairobi*. 263p.

Sanginga, N., Okogun, J.A., Vanlauwe, B., & Dashiell, K. (2002). The contribution of nitrogen by promiscuous soybeans to maize based cropping in the moist savanna of Nigeria. *Plant Soil,* 251, 1-9.

Saiyad, M.M. (2014). Effect of liquid bio-fertilizers on yield attributes of brinjal (*Solanum melongena* L.). *Trends in Biosciences,* 7(22):3754-3756.

Satyanarayana, V., Prasad, P.V.V., Murthy, V.R.K., & Boote, K.J. (2002). Influence of integrated use of farm yard manure and ignoring fertilizers on yield and yield components on irrigated lowland rice. *Journal of plant nutrition,* 25(10):2081-2090.

Savin, R., Slafer, G.A., Cossani, C.M., Abeledo, L.G., & Sadras, V.O. (2015). Cereal yield in Mediterranean-type environments: challenging the paradigms on terminal drought, the adaptability of barley vs wheat and the role of nitrogen fertilization. Applications for Genetic Improvement and Agronomy, 141-158. *Crop Physiology (2nd Edition),* Published by academic Press. https://doi.org/10.1016/B978-0-12-417104-6.00007-8.

Serme, I. (2014). Growth and yield of Sorghum under different conservation tillage and water and nutrient management practices in the South Sudan Zone of Burkina Faso. *Unpublished PhD Thesis.* Kumasi University, Ghana.

Seymour, M., Kirkegaard, J.A., Peoples, M.B., White, P.F., French, R.J., & van Burgel, A. (2012). Break-crop benefits to wheat in Western Australia - insights from over three decades of research. *Crop and Pasture Science,* 63, 1-16.

Schmidt, J., DeJoia, A.J., Ferguson, R., Taylor, R.K., Young, R.K., & Havlin, J. (2002). Corn yield response to nitrogen at multiple in-field locations. *Agronomy Journal,* 94, 798 – 806.

Shoji, S., Delegado, J., Mosier, A. R., & Miura, Y. (2001). Controlled release fertilizers and nitrification inhibitors to increase nitrogen use efficiency and to conserve air and water quality. *Soil Scienc and Plant Analysis,* 32, 1051–1070.

Schroeder, J. J., Neeteson, J. J., Oenema, O., & Struik, P. C. (2000). Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. *Field Crops Research,* 66, 151–164.

Sharma, L.K., & Bali, S.K. (2018). A Review of Methods to Improve Nitrogen Use Efficiency in Agriculture. *Sustainability,* 10, 51.

Sharma, P., Abrol, V., & Sharma, R.K. (2011). Impact of tillage and mulch management on economics, energy requirement and crop performance in maize-wheat rotation in rain-fed sub-humid Inceptisols in India. *European Journal of Agronomy*, 34, 46-51.

Shivay, Y. S., Prasad, R., Singh, S., & Sharma, S. N. (2001). Coating of prilled urea with neem (*Azadirachta indica*) for efficient nitrogen use in lowland transplanted rice (*Oryza sativa*). *Indian Journal of Agronomy*, 46, 453–457.

Siahpoosh, M.R., & Dehghanian, E. (2012). Water Use Efficiency, Transpiration Efficiency, and Uptake Efficiency of Wheat during Drought. *Agronomy Journal,* 104, 1238-1243.

Silunge, F.R., Graef, F., Bellinggrathh – Kimura, S.D., Tumbo, S.D., Kahimba, F.C., & Lana, M.A. (2018). Crop Upgrading Strategies and Modelling for Rainfed Cereals in a Semi-Arid Climate - A Review. *Water, 10*(4): 356. https://doi.org/10.3390/w10040356.

Silva, C. L., Benin, G., Bornhofen, E., Beche, E., Todeschini, M. H., & Milioli, A. S. (2014). Nitrogen use efficiency is associated with chlorophyll content in Brazilian spring wheat. *Australian Journal of Crop Science,* 8, 957-964.

Singh, S.S., Singh, A.K., & Sundaram, P.K. (2015). Agrotechnological options for upscaling agricultural productivity in Eastern Indogangetic plains under impending climate change situations: A review. *Journal of Agrisearch,* 1(2): 55 - 65.

Singh, L., Mirza, B., Sabia, A., Sameera, Q., Bilala, L., Purshotam, S., & Parmeet, S. (2014). Efficient techniques to increase water use efficiency under rainfed Eco-systems. *Journal of AgriSearch,* 1(4): 193 - 200.

Singh, B., Singh, V., Singh, Y., Thindm, H.S., Kumar, A., Gupta, R.K., & Kaul, A. (2012). Fixed-time adjustable dose site-specific nitrogen management in transplanted irrigated rice (*Oryza sativa* L.) in South Asia. *Field Crop Research* 126, 63-69.

Singh, G., Jalota, S.K., & Singh, Y. (2007). Manuring and residue management effects on physical properties of a soil under the rice wheat system in Punjab, India. *Soil and Tillage Research,* 94:229-238.

Sitienei, R., Onwonga, R.N., Lelei, J.J., & Kamoni, P. (2017). Use of Dolichos (*Lablab purpureus* L.) and Combine Fertilizers enhance Soil Nutrient Availability, and Maize (*Zea mays* L.) Yield in Farming Systems of Kabete Sub-County, Kenya. Agricultural Science Research Journal, 7(2): 47 – 61.

Soledad, E., Carlos, O., Erick, Z., Iván, M., & Alejandro, P. (2015). Contribution of legumes to the availability of soil nitrogen and its uptake by wheat in Mediterranean environments of central Chile. *Chilean Journal of Agricultural Research,* 75(1): 0718-5839. http://dx.doi.org/10.4067/S0718-58392015000100016.

Soon, Y.K., Clayton, G.W., & Rice, W.A. (2001). Tillage and previous crop effects on dynamics of nitrogen in a wheat–soil system. *Agronomy Journal*, 93, 842-849.

Spiertz, J.H.J. (2010). Nitrogen, sustainable agriculture and food security: a review. *Agronomy for Sustainable Development,* 30, 43 - 55. https://doi.org/10.1051/agro:2008064.

Srinivasrao, C.H., & Gopinath, K.A. (2016). Resilient rainfed technologies for drought mitigation and sustainable food security. *Mausam Journal* (Formerly Indian *Journal* of Meteorology, Hydrology & Geophysics)*,* 6767, 169 - 182.

Srinivasrao, C.H., Gopinath, K.A., Prasad, J.V.N.S., Prasannakumar, C. & Kumar, S.A. (2016).

Climate Resilient Villages for Sustainable Food Security in Tropical India: Concept, Process, Technologies, Institutions, and Impacts. *Advances in Agronomy,* 140, 9780128046913. DO: 10.1016/bs.agron.2016.06.003.

Stagnari, F., Maggio, A., Galieni, A., & Pisante, M. (2017). Multiple benfits of legumes for agriculture sustainability: an overview. *Chemical and Biological Technologies in. Agriculture*, 4, 2. DOI 10.1186/s40538-016-0085-1.

Stahl, A., Friedt, W., Wittkop, B., & Snowdon, R. J. (2016). Complementary diversity for nitrogen uptake and utilization efficiency reveals broad potential for increased sustainability of oilseed rape production. *Plant and Soil,* 400, 245-262.

Steel, R. G. D., & Torrie, J. H. (1960). *Principles and Procedures of Statistics. (With special Reference to the Biological Sciences.)* McGraw-Hill Book Company, New York, Toronto, London, 481 S., 15 Abb.; 81 s 6 d.

Stuart, D., Schewe, D., & McDermott, M. (2014). Reducing Nitrogen Fertilizer Application as a Climate Change Mitigation Strategy: Understanding Decision Making and Potential Barriers to change in the US. *Land Use Policy,* 36, 210 - 218. DO: 10.1016/ j.landusepol .2013.08.011.

Subhan, A., Khan, Q.U., Mansoor, M., & Khan, M.J. (2017). Effect of Organic and Inorganic Fertilizer on the Water Use Efficiency and Yield Attributes of wheat under Heavy Textured Soil. *Sarhad Journal of Agriculture,* 33(4): 582 - 590. DOI: 10.17582 /journal.sja/2017/33.4.582.590.

Sutton, M.A., Bleeker, A., Howard, C.M., Bekunda, M., Grizzetti, B., de Vries, W., Grinsven, H.J.M., Abrol, Y.P., Adhya, T.K., Billen, G., Davidson, E.A., Datta, A., Diaz, R., Erisman, J.W., Liu, X.J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R.W., Sims, T., Westhoek, H., & Zhang, F.S. (2013). Our Nutrient World: The challenge to produce more food and energy with less pollution. Global Overview of Nutrient Management. *Centre for Ecology and Hydrology, Edinburgh on behalf of the Global Partnership on Nutrient Management and the International Nitrogen Initiative*. Available at:http://initrogen.org/index.php/publications/our-nutrient-world/

Sutton, M.A., Oenema, O., Erisman, J.W., Leip, A., van Grinsven, H., & Winiwarter, W. (2011). Too much of a good thing. *Nature,* 472, 159-161.

Swain, E.Y., Rempelos, L., Orr, C.H., Hall, G., Chapman, R., Almadni, M., Stockdale, E.A., Kidd, J., Leifert, C., & Cooper, J.M. (2014). Optimizing nitrogen use efficiency in wheat and potatoes: interactions between genotypes and agronomic practices. *Euphytica,* 199, 119–136. https://doi.org/10.1007/s10681-014-1181-6.

Tadesse, W., Bishaw, Z., & Assefa, S. (2019). "Wheat production and breeding in Sub-Saharan Africa: Challenges and opportunities in the face of climate change", *International Journal of Climate Change Strategies and Management*, 11(5): 696-715. DOI - 10.1108/IJCCSM-02-2018-0015.

Temesgen, B., Stroosnijder, L., & Birhanu, B. (2012). To tie or not to tie ridges for water conservation in Rift Valley drylands of Ethiopia. *Soil and Tillage Research Journal,* 124, 83 – 94. DO - 10.1016/j.still.2012.05.006.

Thomas, C.L., Acquah, G.E., Whitmore, A.P., McGrath, S.P., & Haefele, S.M. (2019). The Effect of Different Organic Fertilizers on Yield and Soil and Crop Nutrient Concentrations. *Agronomy*, 9, 776; DOI:10.3390/agronomy9120776

Thorup-Kristensen, K., & Kirkegaard, J. (2016). Root system - based limits to agricultural productivity and efficiency: the farming system context. *Annals of Botany,* 118(4): 573 – 592. 10.1093/aob/mcw122.

Tilman, D., Balzer, C., Hill, J., & Befort, B. (2011). Global food demand and the sustainable Intensification of agriculture. Proceedings of the National Academy of Sciences, 108, 20260–20264.

Tron, S., Bodner, G., Laio, F., Ridolfi, L., & Leitner, D. (2015). Can diversity in root architecture explain plant water use efficiency? A modeling study. *Ecological Modelling,* 312, 200-210.

Uribelarrea, M., Below, F.E., & Moose, S.P. (2007). Divergent selection for grain protein affects nitrogen use in maize. *Field Crops Research,* 100, 82 – 90.

Umesha, C., Sridhara, C. J., & Kumarnaik, A. H. (2017). Recent Forms of Fertilizers and Their Use to Improve Nutrient Use Efficiency and To Minimize Environmental Impacts, *Int. J. Pure Applied Biosciences,* 5(2): 858-863. DOI: http://dx.doi.org/10.18782/2320-7051.2739

Ullah, H., Santiago-Arenas, R., Ferdous, Z., Attia, A., & Datta, A. (2019). Improving water use efficiency, nitrogen use efficiency, and radiation use efficiency in field crops under drought stress: A review. *Advances in Agronomy,* 156, 109-157.

https://doi.org/10.1016/bs.agron.2019.02.002

Valenzuela, H., & Smith, J. (2002). *Sustainable agriculture green manure crops.* SA-GM-7. Cooperative Extension Service, College of Tropical Agric. and Human Resources, University of Hawaii at Manoa. Available at:http://www.ctahr.hawaii.edu/oc/freepubs/pdf/GreenManureCrops/lablab.pdf.

Vance, E.D., Brookes, P.C., & Jenkinson, D.S. (1987). An extraction method for measuring soil microbial biomass C. *Soil Biology and Biochemistry*, 19(6): 703-707, Printed in Great Britain.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., & Sanginga, N. (2010). Integrated soil fertility management. Operational definition and consequences for implementation and dissemination. *Outlook in Agriculture,* 39(1): 17-24.

Van Sanford, D.A., & MacKown, C. T. (1986). Variation in nitrogen use efficiency among soft red winter wheat genotypes. *Theoretical and Applied Genetics*, 72, 158-163.

Varvel, G.E., & Wilhelm, W. (2018). Soybean nitrogen contribution to corn and sorghum in Western Corn Belt rotations. *Agronomy Journal,* 95, 1220 - 1225.https://doi.org/10.2134/agronj2003.1220.

Varvel, G.E., & Peterson, T.A. (1991). Nitrogen Fertilizer Recovery by Grain Sorghum in Monoculture and Rotation Systems. *Agronomy Journal,* 83, 617-622.

Verde, B.S., Danga, B.O., & Mugwe, J.N. (2013). Effects of manure, lime and mineral P fertilizer on soybean yields and soil fertility in a humic nitisol in the Central Highlands of Kenya. *International Journal of Agricultural Science Research,* 2(9): 283-291.

Volpe, V., Giovannetti, M., Sun, X.G., Fiorilli, V., & Bonfante, P. (2016). The phosphate transporters LjPT4 and MtPT4 mediate early root responses to phosphate status in non mycorrhizal roots. *Plant Cell and Environment, 39*, 660–671.

Wallace, J. S. (2000). Increasing agricultural water use efficiency to meet future food production. *Agricultural Ecosystemand Environment,* 82, 105–110. DOI-10.1016/S0167-8809(00)00220-6

Walley. F.L., Clayton, G.W., Miller, P.R., Carr, P.M., & Lafond, G.P. (2007). Nitrogen economy of pulse crop production in the Northern Great Plains. *Agronomy Journal,* 99, 1710–1821.

Wani, B.A., Ram, M., Yasin, A., & Singh, E. (2011). Physiological traits in integration with yield and yield components in wheat (*Triticum aestivum* L.) study of their genetic variability and correlation. *Asian Journal of Agricultural Research*, 5, 194-200.

Westhoek, H., Lesschen, J.P., Rood, T., Wagner, S., De Marco, A., Murphy-Bokern, D., Leip, A., van Grinsven, H., Sutton, M.A., & Oenema, O. (2014). Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. *Global Environmental Change-Human and Policy Dimensions,* 26, 196-205.

Williams, L.E., & Miller A.J. (2001). Transporters responsible for the uptake and partitioning of nitrogenous solutes. *Annual Review of Plant Physiology and Plant Molecular Biology,* 52*,* 659–688.

Wiyo, K.A., Kasomekera, Z.M., & Feyen, J. (2000). Effect of tie-ridging on soil water status of a maize crop under Malawi conditions. *Agricultural Water Management,* 45(2): 101 - 125. DOI: 10.1016/S0378-3774(99)00103-1.

Worm, J., & Hattum, T. (2006). Agrodok 43: Rainwater Harvesting for Domestic Use. *Agromisa Foundation and CTA,* Wageningen, 85p.

Xinhuanet. (2021). *Kenya's wheat production hit 270,000 tons in 2020.* Availbale: http://www.xinhuanet.com/english/africa/2021-05/11/c_139939237.htm)

Yamoah, C.F., Varvel, G.E., Waltman, W.J., & Francis, C.A. (1998). Long-term nitrogen use and nitrogen-removal index in continuous crops and rotations. *Field Crops Research,* 57, 15 - 27.

Yang, T., Siddique, K.H.M., & Liu, K. (2020). Cropping systems in agriculture and their impact on soil health-A review. *Global Ecology and Conservation*, 23. https://doi.org/10.1016/j.gecco.2020.e01118.

Yassen, A.A., El-Hardy, M.A., & Zaghloul, S.M. (2006). Replacement part of mineral N fertilizer by organic ones and its effect on wheat plant under water regime conditions. *World Journal of Agricultural Science,* 2(4): 421- 428.

Yazar, A., & Ali, A. (2016). Water Harvesting in Dry Environments. In book: *Innovations in Dryland Agriculture, M. Farooq and K. Siddique (eds),* 49 -98pp. Springer International Publishing.

Yoseph, T., & Gebre, W. (2015). Evaluation of different moisture conservation practices on growth, yield and yield components of sorghum at Alduba, southern Ethiopia. *Research Journal of Agriculture and Environmental Management,* 4(3): 169 - 173.

Yusuf, A.A., Abaidoo, R.C., Iwuafor, E.N.O., Olufajo, O.O., & Sanginga, N. (2009a). Rotation effects of grain legumes and fallow on maize yield, microbial biomass and chemical properties of an Alfisol in the Nigerian savanna. *Agricultural Ecosystem and Environment,* 129, 325 - 331.

Yusuf, A.A., Iwuafor, E.N.O., Abaidoo, R.C., Olufajo, O.O., & Sanginga, N. (2009b). Grain legume rotation benefits to maize in the northern Guinea savanna of Nigeria: Fixed-nitrogen vs. other rotation effects. *Nutrition Cyclying and Agroecosyst,* 84, 129 - 139.

Zander, P., Amjath-Babu, T.S., Preissel, S., Reckling, M., Bues, A., & Schläfke, N. (2016). Grain legume decline and potential recovery in European agriculture: a review. *Agronomy for Sustainable Development*, 36, 26p.

Zeyege, A.D., Guzman, C.D., Chanie, D., Ayana, E.K., Tilahun, S.A., Steenhuis, T.S., & Tebebu, T.Y. (2015). The impact of large scale Government-led soil and water conservation on Runoff and soil loss in the Debre Mani watershed. In: *Water Amart Agriculture in East Africa (eds. Allan Nicol, Simon Langan, Michael Victor and Julian Gonsalves),* Addis Ababa, 97 – 100.

Zhang, X.Y., Chen, S.Y., Sun, H.Y., Wang, Y.M., & Shao, L.W. (2010). Water use efficiency and associated traits in winter wheat cultivars in the North China Plain. *Agricultural Water Management,* 97, 1117 - 1125.

Zhang, X.Y., Pei, D., Chen, S.Y., Sun, H.Y., & Yang, Y.H. (2006). Performance of double-cropped winter wheat summer maize under minimum irrigation in the North China Plain. *Agronomy Journal,* 98, 1620 - 1626.

Zhang, D., Yao, P., Na, Z., Cao, W., Zhang, S., Li, Y., & Gao, Y. (2016). Soil water balance and water use efficiency of dryland wheat in different precipitation years in response to green manure approach. *Scientific Report,* 6, 26856. DOI.org//10.1038/srep26856.

Zhang, S., Lovdahl, L., Grip, H., Tong, Y., Yang, X., & Wang, Q. (2009). Effects of mulching and catch cropping on soil temperature, soil moisture and wheat yield on the Loess Plateau of China. *Soil and Tillage Research,* 102,78 - 86.

APPENDICES

Appendix I: Mean squares showing the effects of factors and their interactions on soil N, soil organic carbon (SOC), soil moisture, soil temperature and total water use (TWU)

Source of variation	Df	Soil organic carbon	Soil N	Soil Temperature	Soil moisture	Total water use
Rep	2	9.0713	0.08467	296.876	7165	0.7198
Water harvesting (WH)	1	2.7333	0.00027	7.358	117.5	0.0166
Residual	2	1.3202	0.07959	9.567	181.3	0.0245
Crop rotation (CR)	3	0.1952	0.0071	165.176***	2885.5***	0.2783***
WH x CR	3	0.0151	0.01031	1.38	128.4	0.0119
Residual	12	0.3157	0.01062	2.065	198.3	0.0176
Soil Fertility Management (SFM)	5	0.0226	0.02539	2.848	141.2	0.0120
WH x SFM	5	0.0863	0.01371	1.086	49.1	0.0044
CR x SFM	15	0.1443	0.01695	1.721	205.4	0.0181
WH x CR x SFM	15	0.1918	0.01338	3.426*	269.2	0.0224
Residual	80	0.4451	0.01282	1.601	232.3	0.0204
Season (S)	2	38.4003***	6.39154***	100.526***	98341.2***	1235000***
WH x S	2	8.08***	0.00097	1.068	69	0.0049
CR x S	6	0.2337	0.01166	156.102***	954.7***	0.08588***
SFM x S	10	0.329	0.02054	1.495	192.6	0.0171
WH x CR x S	6	0.2786	0.02334	0.806	20.3	0.0012
WH x SFM x S	10	0.1336	0.00976	1.346	105	0.0084
CR x SFM x S	30	0.246	0.00975	0.543	102.6	0.0079
WH x CR x SFM x S	30	0.2262	0.01291	0.805	103.6	0.0077
Residual	192	0.6928	0.01273	2.185	179.1	0.0157
Total	431					

Appendix II: Mean squares showing the cumulative effects of factors and their interactions on NUE, NUpE, NUtE and WUE

Source of variation	Df	NUE	NU_pE	NU_tE	WUE
Rep	2	272.3	261.4	368.68	2.1486
CR	3	2723.5***	3631.6***	6.17	8.8991**
Residual	6	82.3	129.8	15.89	0.1535
WH	1	301.2	461.8	42.97	0.217
CR.WH	3	259.6	598.8	61.8	5.6175**
Residual	8	169.8	169	37.1	0.564
SFM	5	1182.3***	1495.2**	26.1	8.3332**
CR.SFM	15	591.8***	1130.4**	24.49	2.3477**
WH.SFM	5	168.1	234.2	9.79	2.3796**
CR.WH.SFM	15	144.9	366.2	24.35	0.9516**
Residual	80	146	234.7	16.77	0.2417
Total	143				

Appendix III: Mean squares showing the effect of factors and their interactions on grain yield and biomass

Source of variation	Df	Grain Yield	Biomass
Rep stratum	2	170559	1011567
Water Harvesting (WH)	1	68885	278282147***
Residual	6	96637	2486833
Crop Rotation (CR)	3	4043216**	3023230
WH x CR	3	1405269**	327497
Residual	8	83443	884697
Soil Fertility Management (SFM)	5	2084977**	1455007
CR x SFM	15	414976**	1138137
WH x SFM	5	516217**	564371
CR x WH x SFM	15	191432**	1583192
Residual	80	48198	922779
Total	**143**		

Appendix IV: Treatment combinations for 1st season (2014)

Treatment No.	Main Plot = Water Harvesting (WH)	Sub-Plot = Crop Rotation (CR)- Crop Species	Sub-Sub- Plot = Soil Fertility Management (SFM)
1	WH1 –Flat bed	CR1=Wheat	SFM4= 25 kg N ha^{-1}
2	WH1 –Flat bed	CR1=Wheat	SFM6= 75 kg N ha^{-1}
3	WH1 –Flat bed	CR1=Wheat	SFM2 = 5 t FYM ha^{-1}
4	WH1 –Flat bed	CR1=Wheat	SFM1 = Control
5	WH1 –Flat bed	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
6	WH1 –Flat bed	CR1=Wheat	SFM5 = 50 kg N ha^{-1}
7	WH1 –Flat bed	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
8	WH1 –Flat bed	CR1=Wheat	SFM1= Control
9	WH1 –Flat bed	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
10	WH1 –Flat bed	CR1=Wheat	SFM4 = 25kg N ha^{-1}
11	WH1 –Flat bed	CR1=Wheat	SFM4 = 25kg N ha^{-1}
12	WH1 –Flat bed	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
13	WH2- Tie Ridge	CR1=Wheat	SFM5 = 50kg N ha^{-1}
14	WH2- Tie Ridge	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
15	WH2- Tie Ridge	CR1=Wheat	SFM1 = Control
16	WH2- Tie Ridge	CR1=Wheat	SFM4 = 25kg N ha^{-1}
17	WH2- Tie Ridge	CR1=Wheat	SFM6 = 75kg N ha^{-1}
18	WH2- Tie Ridge	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
19	WH2- Tie Ridge	CR1=Wheat	SFM5 = 50kg N ha^{-1}
20	WH2- Tie Ridge	CR1=Wheat	SFM6 = 75kg N ha^{-1}
21	WH2- Tie Ridge	CR1=Wheat	SFM4 = 25kg N ha^{-1}
22	WH2- Tie Ridge	CR1=Wheat	SFM1 = Control
23	WH2- Tie Ridge	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
24	WH2- Tie Ridge	CR1=Wheat	SFM1 = Control

25	WH1 –Flat bed	CR1=Wheat	SFM5 = 50kg N ha^{-1}
26	WH1 –Flat bed	CR1=Wheat	SFM2=5t FYM ha^{-1}
27	WH1 –Flat bed	CR1=Wheat	SFM1 = Control
28	WH1 –Flat bed	CR1=Wheat	SFM6 = 75kg N ha^{-1}
29	WH1 –Flat bed	CR1=Wheat	SFM5 = 50kg N ha^{-1}
30	WH1 –Flat bed	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
31	WH1 –Flat bed	CR1=Wheat	SFM1= Control
32	WH1 –Flat bed	CR1=Wheat	SFM6 = 75kg N ha^{-1}
33	WH1 –Flat bed	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
34	WH1 –Flat bed	CR1=Wheat	SFM5 = 50kg N ha^{-1}
35	WH1 –Flat bed	CR1=Wheat	SFM6 = 75kg N ha^{-1}
36	WH1 –Flat bed	CR1=Wheat	SFM4 = 25kg N ha^{-1}
37	WH2= Tie ridge	CR1=Wheat	SFM1=Control
38	WH2= Tie ridge	CR1=Wheat	SFM6 = 75kg N ha^{-1}
39	WH2= Tie ridge	CR1=Wheat	SFM4 = 25kg N ha^{-1}
40	WH2= Tie ridge	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
41	WH2= Tie ridge	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
42	WH2= Tie ridge	CR1=Wheat	SFM5 = 50kg N ha^{-1}
43	WH2= Tie ridge	CR1=Wheat	SFM4 = 25kg N ha^{-1}
44	WH2= Tie ridge	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
45	WH2= Tie ridge	CR1=Wheat	SFM3 = 2.5 t GM ha^{-1}
46	WH2= Tie ridge	CR1=Wheat	SFM2 = 5t FYM ha^{-1}
47	WH2= Tie ridge	CR1=Wheat	SFM6 = 75kg N ha^{-1}
48	WH2= Tie ridge	CR1=Wheat	SFM5 = 50kg N ha^{-1}

Appendix V: Treatment combinations for the 2nd season (2015)

Treatment No.	Main Plot = Water Harvesting (WH)	Sub-Plot Crop Rotation (CR) - Crop Species	Sub-Sub- Plot= Soil Fertility Management (SFM)
1	WH1 –Flat bed	CR1=Dolichos	SFM4= 25 kg Nha^{-1}
2	WH1 –Flat bed	CR2=Greenpea	SFM6= 75 kg N ha^{-1}
3	WH1 –Flat bed	CR3=Potato	SFM2 = 5 t FYM ha^{-1}
4	WH1 –Flat bed	CR4=Wheat	SFM1 = Control
5	WH1 –Flat bed	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
6	WH1 –Flat bed	CR3=Potato	SFM5 = 50 kg N ha^{-1}
7	WH1 –Flat bed	CR2=Greenpea	SFM3 = 2.5 t GM ha^{-1}
8	WH1 –Flat bed	CR1=Dolichos	SFM1= Control
9	WH1 –Flat bed	CR1=Dolichos	SFM4 = 25kg N ha^{-1}
10	WH1 –Flat bed	CR2=Greenpea	SFM5 = 50kg N ha^{-1}
11	WH1 –Flat bed	CR3=Potato	SFM2 = 5t FYM ha^{-1}
12	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}
13	WH2- Tie Ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}
14	WH2- Tie Ridge	CR3=Potato	SFM3 = 2.5 t GM ha^{-1}
15	WH2- Tie Ridge	CR2=Greenpea	SFM1 = Control
16	WH2- Tie Ridge	CR1=Dolichos	SFM4 = 25kg N ha^{-1}
17	WH2- Tie Ridge	CR1=Dolichos	SFM6 = 75kg N ha^{-1}
18	WH2- Tie Ridge	CR2=Greenpea	SFM2 = 5t FYM ha^{-1}
19	WH2- Tie Ridge	CR3=Potato	SFM3 = 2.5t GM ha^{-1}
20	WH2- Tie Ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}
21	WH2- Tie Ridge	CR4=Wheat	SFM4 = 25kg N ha^{-1}
22	WH2- Tie Ridge	CR3=Potato	SFM1 = Control
23	WH2- Tie Ridge	CR2=Greenpea	SFM2 = 5t FYM ha^{-1}
24	WH2- Tie Ridge	CR1=Dolichos	SFM6 = 75kg N ha^{-1}
25	WH1 –Flat bed	CR1=Dolichos	SFM5 = 50kg N ha^{-1}
26	WH1 –Flat bed	CR2=Greenpea	SFM2 = 5t FYM ha^{-1}
27	WH1 –Flat bed	CR3=Potato	SFM1= Control
28	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}

29	WH1 –Flat bed	CR4=Wheat	SFM5 = 50kg N ha^{-1}
30	WH1 –Flat bed	CR3=Potato	SFM3 = 2.5 t GM ha^{-1}
31	WH1 –Flat bed	CR2=Greenpea	SFM1= Control
32	WH1 –Flat bed	CR1=Dolichos	SFM6 = 75kg N ha^{-1}
33	WH1 –Flat bed	CR1=Dolichos	SFM2 = 5t FYM ha^{-1}
34	WH1 –Flat bed	CR2=Greenpea	SFM5 = 50kg N ha^{-1}
35	WH1 –Flat bed	CR3=Potato	SFM6 = 75kg N ha^{-1}
36	WH1 –Flat bed	CR4=Wheat	SFM4 = 25kg N ha^{-1}
37	WH2= Tie ridge	CR4=Wheat	SFM1 = Control
38	WH2= Tie ridge	CR3=Potato	SFM6 = 75kg N ha^{-1}
39	WH2= Tie ridge	CR2=Greenpea	SFM4 = 25kg N ha^{-1}
40	WH2= Tie ridge	CR1=Dolichos	SFM2 = 5t FYM ha^{-1}
41	WH2= Tie ridge	CR1=Dolichos	SFM3 = 2.5 t GM ha^{-1}
42	WH2= Tie ridge	CR2=Greenpea	SFM5 = 50kg N ha^{-1}
43	WH2= Tie ridge	CR3=Potato	SFM4 = 25kg N ha^{-1}
44	WH2= Tie ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
45	WH2= Tie ridge	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
46	WH2= Tie ridge	CR3=Potato	SFM2 = 5t FYM ha^{-1}
47	WH2= Tie ridge	CR2=Greenpea	SFM6 = 75kg N ha^{-1}
48	WH2= Tie ridge	CR1=Dolichos	SFM5 = 50kg N ha^{-1}

Appendix VI: Treatment combinations for the 3rd season (2016)

Treatment No.	Main Plot = Water Harvesting (WH)	Sub-Plot Crop Rotation (CR) - Crop Species	Sub-Sub- Plot= Soil Fertility Management (SFM)
1	WH1 –Flat bed	CR4=Wheat	SFM4= 25 kg Nha^{-1}
2	WH1 –Flat bed	CR4=Wheat	SFM6= 75 kg N ha^{-1}
3	WH1 –Flat bed	CR4=Wheat	SFM2 = 5 t FYM ha^{-1}
4	WH1 –Flat bed	CR4=Wheat	SFM1 = Control
5	WH1 –Flat bed	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
6	WH1 –Flat bed	CR4=Wheat	SFM5 = 50 kg N ha^{-1}
7	WH1 –Flat bed	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
8	WH1 –Flat bed	CR4=Wheat	SFM1= Control
9	WH1 –Flat bed	CR4=Wheat	SFM4 = 25kg N ha^{-1}
10	WH1 –Flat bed	CR4=Wheat	SFM5 = 50kg N ha^{-1}
11	WH1 –Flat bed	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
12	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}
13	WH2- Tie Ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}
14	WH2- Tie Ridge	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
15	WH2- Tie Ridge	CR4=Wheat	SFM1 = Control
16	WH2- Tie Ridge	CR4=Wheat	SFM4 = 25kg N ha^{-1}
17	WH2- Tie Ridge	CR4=Wheat	SFM6 = 75kg N ha^{-1}
18	WH2- Tie Ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
19	WH2- Tie Ridge	CR4=Wheat	SFM3 = 2.5t GM ha^{-1}
20	WH2- Tie Ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}
21	WH2- Tie Ridge	CR4=Wheat	SFM4 = 25kg N ha^{-1}
22	WH2- Tie Ridge	CR4=Wheat	SFM1 = Control
23	WH2- Tie Ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
24	WH2- Tie Ridge	CR4=Wheat	SFM6 = 75kg N ha^{-1}
25	WH1 –Flat bed	CR4=Wheat	SFM5 = 50kg N ha^{-1}
26	WH1 –Flat bed	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
27	WH1 –Flat bed	CR4=Wheat	SFM1= Control
28	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}

29	WH1 –Flat bed	CR4=Wheat	SFM5 = 50kg N ha^{-1}
30	WH1 –Flat bed	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
31	WH1 –Flat bed	CR4=Wheat	SFM1= Control
32	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}
33	WH1 –Flat bed	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
34	WH1 –Flat bed	CR4=Wheat	SFM5 = 50kg N ha^{-1}
35	WH1 –Flat bed	CR4=Wheat	SFM6 = 75kg N ha^{-1}
36	WH1 –Flat bed	CR4=Wheat	SFM4 = 25kg N ha^{-1}
37	WH2= Tie ridge	CR4=Wheat	SFM1 = Control
38	WH2= Tie ridge	CR4=Wheat	SFM6 = 75kg N ha^{-1}
39	WH2= Tie ridge	CR4=Wheat	SFM4 = 25kg N ha^{-1}
40	WH2= Tie ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
41	WH2= Tie ridge	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
42	WH2= Tie ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}
43	WH2= Tie ridge	CR4=Wheat	SFM4 = 25kg N ha^{-1}
44	WH2= Tie ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
45	WH2= Tie ridge	CR4=Wheat	SFM3 = 2.5 t GM ha^{-1}
46	WH2= Tie ridge	CR4=Wheat	SFM2 = 5t FYM ha^{-1}
47	WH2= Tie ridge	CR4=Wheat	SFM6 = 75kg N ha^{-1}
48	WH2= Tie ridge	CR4=Wheat	SFM5 = 50kg N ha^{-1}

Appendix VII: Field Plan For the 2014-Season1

PLOT 1 TRT 1 W	PLOT 2 TRT 2 W	PLOT 3 TRT 3 W	PLOT 4 TRT 4 W
PLOT 8 TRT 8 W	PLOT 7 TRT 7 W	PLOT 6 TRT 6 W	PLOT 5 TRT 5 W
PLOT 9 TRT 9 W	PLOT 10 TRT 10 W	PLOT 11 TRT 11 W	PLOT 12 TRT 12 W
PLOT 16 TRT 16 W	PLOT 15 TRT 15 W	PLOT 14 TRT 14 W	**PLOT 13** **TRT 13** W
PLOT 17 TRT 17 W	PLOT 18 TRT 18 W	PLOT 19 TRT 19 W	PLOT 20 TRT 20 W
PLOT 24 TRT 24 W	PLOT 23 TRT 23 W	PLOT 22 TRT 22 W	PLOT 21 TRT 21 W

PLOT 96 TRT 48 W	PLOT 95 TRT 47 W	PLOT 94 TRT 46 W	PLOT 93 TRT 45 W
PLOT 89 TRT 41 W	PLOT 90 TRT 42 W	PLOT 91 TRT 43 W	PLOT 92 TRT 44 W
PLOT 88 TRT 40 W	PLOT 87 TRT 39 W	PLOT 86 TRT 38 W	PLOT 85 TRT 37 W
PLOT 81 TRT 33 W	PLOT 82 TRT 34 W	PLOT 83 TRT 35 W	PLOT 84 TRT 36 W
PLOT 80 TRT 32 W	PLOT 79 TRT 31 W	PLOT 78 TRT 30 W	PLOT 77 TRT 29 W
PLOT 73 TRT 25 W	PLOT 74 TRT 26 W	PLOT 75 TRT 27 W	PLOT 76 TRT 28 W

PLOT 97 TRT1 W	PLOT 98 TRT 2 W	PLOT 99 TRT 3 W	PLOT 100 TRT 4 W
PLOT 104 TRT 8 W	PLOT 103 TRT 7 W	PLOT 102 TRT 6 W	PLOT 101 TRT 5 W
PLOT 105 TRT9 W	PLOT 106 TRT 10 W	PLOT 107 TRT 11 W	PLOT 108 TRT 12 W
PLOT 112 TRT 16 W	PLOT 111 TRT 15 W	PLOT 110 TRT 14 W	PLOT 109 TRT 13 W
PLOT 113 TRT 17 W	PLOT 114 TRT 18 W	PLOT 115 TRT 19 W	PLOT 116 TRT 20 W
PLOT 120 TRT 24 W	PLOT 119 TRT 23 W	PLOT 118 TRT 22 W	PLOT 117 TRT 21 W

PLOT 25 TRT 25 W	PLOT 26 TRT 26 W	PLOT 27 TRT 27 W	PLOT 28 TRT 28 W
PLOT 32 TRT 32 W	PLOT 31 TRT 31 W	PLOT 30 TRT 30 W	PLOT 29 TRT 29 W
PLOT 33 TRT 33 W	PLOT 34 TRT 34 W	PLOT 35 TRT 35 W	PLOT 36 TRT 36 W
PLOT 40 TRT 40 W	PLOT 39 TRT 39 W	PLOT 38 TRT 38 W	PLOT 37 TRT 37 W
PLOT 41 TRT 41 W	PLOT 42 TRT 42 W	PLOT 43 TRT 43 W	PLOT 44 TRT 44 W
PLOT 48 TRT 48 W	PLOT 47 TRT47 W	PLOT 46 TRT 46 W	PLOT 45 TRT 45 W

PLOT 72 TRT 24 W	PLOT 71 TRT 23 W	PLOT 70 TRT 22 W	PLOT 69 TRT 21 W
PLOT 65 TRT 17 W	PLOT 66 TRT 18 W	PLOT 67 TRT 19 W	PLOT 68 TRT 20 W
PLOT 64 TRT 16 W	PLOT 63 TRT 15 W	PLOT 62 TRT 14 W	PLOT 61 TRT 13 W
PLOT 57 TRT 9 DOL	PLOT 58 TRT 10 W	PLOT 59 TRT 11 W	PLOT 60 TRT 12 W
PLOT 56 TRT 8 W	PLOT 55 TRT 7 W	PLOT 54 TRT 6 W	PLOT 53 TRT 5 W
PLOT 49 TRT 1 W	PLOT 50 TRT 2 W	PLOT 51 TRT 3 W	PLOT 52 TRT 4 W

PLOT 121 TRT 25 W	PLOT 122 TRT 26 W	PLOT 123 TRT 27 W	PLOT 124 TRT 28 W
PLOT 128 TRT 32 W	PLOT 127 TRT 31 W	PLOT 126 TRT 30 W	PLOT 125 TRT 29 W
PLOT 129 TRT 33 W	PLOT 130 TRT 34 W	PLOT 131 TRT 35 W	PLOT 132 TRT 36 W
PLOT 136 TRT 40 W	PLOT 135 TRT 39 W	PLOT 134 TRT 38 W	PLOT 133 TRT 37 W
PLOT 137 TRT 41 W	PLOT 138 TRT 42 W	PLOT 139 TRT 43 W	PLOT 140 TRT 44 W
PLOT 144 TRT 48 W	PLOT 143 TRT 47 W	PLOT 142 TRT 46 W	PLOT 141 TRT 45 W

Appendix VIII: Field Plan For the 2015-Season2

PLOT 1 TRT 1 DOL	PLOT 2 TRT 2 GP	PLOT 3 TRT 3 POT	PLOT 4 TRT 4 W
PLOT 8 TRT 8 DOL	PLOT 7 TRT 7 GP	PLOT 6 TRT 6 POT	PLOT 5 TRT 5 W
PLOT 9 TRT 9 DOL	PLOT 10 TRT 10 GP	PLOT 11 TRT 11 POT	PLOT 12 TRT 12 W
PLOT 16 TRT 16 DOL	PLOT 15 TRT 15 GP	PLOT 14 TRT 14 POT	**PLOT 13** **TRT 13** W
PLOT 17 TRT 17 DOL	PLOT 18 TRT 18 GP	PLOT 19 TRT 19 POT	PLOT 20 TRT 20 W
PLOT 24 TRT 24 DOL	PLOT 23 TRT 23 GP	PLOT 22 TRT 22 POT	PLOT 21 TRT 21 W

PLOT 96 TRT 48 DOL	PLOT 95 TRT 47 GP	PLOT 94 TRT 46 POT	PLOT 93 TRT 45 W
PLOT 89 TRT 41 DOL	PLOT 90 TRT 42 GP	PLOT 91 TRT 43 POT	PLOT 92 TRT 44 W
PLOT 88 TRT 40 DOL	PLOT 87 TRT 39 GP	PLOT 86 TRT 38 POT	PLOT 85 TRT 37 W
PLOT 81 TRT 33 DOL	PLOT 82 TRT 34 GP	PLOT 83 TRT 35 POT	PLOT 84 TRT 36 W
PLOT 80 TRT 32 DOL	PLOT 79 TRT 31 GP	PLOT 78 TRT 30 POT	PLOT 77 TRT 29 W
PLOT 73 TRT 25 DOL	PLOT 74 TRT 26 GP	PLOT 75 TRT 27 POT	PLOT 76 TRT 28 W

PLOT 97 TRT1 DOL	PLOT 98 TRT 2 GP	PLOT 99 TRT 3 POT	PLOT 100 TRT 4 W
PLOT 104 TRT 8 DOL	PLOT 103 TRT 7 GP	PLOT 102 TRT 6 POT	PLOT 101 TRT 5 W
PLOT 105 TRT9 DOL	PLOT 106 TRT 10 GP	PLOT 107 TRT 11 POT	PLOT 108 TRT 12 W
PLOT 112 TRT 16 DOL	PLOT 111 TRT 15 GP	PLOT 110 TRT 14 POT	PLOT 109 TRT 13 W
PLOT 113 TRT 17 DOL	PLOT 114 TRT 18 GP	PLOT 115 TRT 19 POT	PLOT 116 TRT 20 W
PLOT 120 TRT 24 DOL	PLOT 119 TRT 23 GP	PLOT 118 TRT 22 POT	PLOT 117 TRT 21 W

PLOT 25 TRT 25 DOL	PLOT 26 TRT 26 GP	PLOT27 TRT 27 POT	PLOT 28 TRT 28 W
PLOT 32 TRT 32 DOL	PLOT 31 TRT 31 GP	PLOT 30 TRT 30 POT	PLOT 29 TRT 29 W
PLOT 33 TRT 33 DOL	PLOT 34 TRT 34 GP	PLOT 35 TRT 35 POT	PLOT 36 TRT 36 W
PLOT 40 TRT 40 DOL	PLOT 39 TRT 39 GP	PLOT 38 TRT 38 POT	PLOT 37 TRT 37 W
PLOT 41 TRT 41 DOL	PLOT 42 TRT 42 GP	PLOT 43 TRT 43 POT	PLOT 44 TRT 44 W
PLOT 48 TRT 48 DOL	PLOT 47 TRT47 GP	PLOT 46 TRT 46 POT	PLOT 45 TRT 45 W

PLOT 72 TRT 24 DOL	PLOT 71 TRT 23 GP	PLOT 70 TRT 22 POT	PLOT 69 TRT 21 W
PLOT 65 TRT 17 DOL	PLOT 66 TRT 18 GP	PLOT 67 TRT 19 POT	PLOT 68 TRT 20 W
PLOT 64 TRT 16 DOL	PLOT 63 TRT 15 GP	PLOT 62 TRT 14 POT	PLOT 61 TRT 13 W
PLOT 57 TRT 9 DOL	PLOT 58 TRT 10 GP	PLOT 59 TRT 11 POT	PLOT 60 TRT 12 W
PLOT 56 TRT 8 DOL	PLOT 55 TRT 7 GP	PLOT 54 TRT 6 POT	PLOT 53 TRT 5 W
PLOT 49 TRT 1 DOL	PLOT 50 TRT 2 GP	PLOT 51 TRT 3 POT	PLOT 52 TRT 4 W

PLOT 121 TRT 25 DOL	PLOT 122 TRT 26 GP	PLOT 123 TRT 27 POT	PLOT 124 TRT 28 W
PLOT 128 TRT 32 DOL	PLOT 127 TRT 31 GP	PLOT 126 TRT 30 POT	PLOT 125 TRT 29 W
PLOT 129 TRT 33 DOL	PLOT 130 TRT 34 GP	PLOT 131 TRT 35 POT	PLOT 132 TRT 36 W
PLOT 136 TRT 40 DOL	PLOT 135 TRT 39 GP	PLOT 134 TRT 38 POT	PLOT 133 TRT 37 W
PLOT 137 TRT 41 DOL	PLOT 138 TRT 42 GP	PLOT 139 TRT 43 POT	PLOT 140 TRT 44 W
PLOT 144 TRT 48 DOL	PLOT 143 TRT 47 GP	PLOT 142 TRT 46 POT	PLOT 141 TRT 45 W

Appendix IX: Field Plan For the 2016 – Season3

PLOT 1 TRT 1 W	PLOT 2 TRT 2 W	PLOT 3 TRT 3 W	PLOT 4 TRT 4 W
PLOT 8 TRT 8 W	PLOT 7 TRT 7 W	PLOT 6 TRT 6 W	PLOT 5 TRT 5 W
PLOT 9 TRT 9 W	PLOT 10 TRT 10 W	PLOT 11 TRT 11 W	PLOT 12 TRT 12 W
PLOT 16 TRT 16 W	PLOT 15 TRT 15 W	PLOT 14 TRT 14 W	**PLOT 13** **TRT 13** W
PLOT 17 TRT 17 W	PLOT 18 TRT 18 W	PLOT 19 TRT 19 W	PLOT 20 TRT 20 W
PLOT 24 TRT 24 W	PLOT 23 TRT 23 W	PLOT 22 TRT 22 W	PLOT 21 TRT 21 W

PLOT 96 TRT 48 W	PLOT 95 TRT 47 W	PLOT 94 TRT 46 W	PLOT 93 TRT 45 W
PLOT 89 TRT 41 W	PLOT 90 TRT 42 W	PLOT 91 TRT 43 W	PLOT 92 TRT 44 W
PLOT 88 TRT 40 W	PLOT 87 TRT 39 W	PLOT 86 TRT 38 W	PLOT 85 TRT 37 W
PLOT 81 TRT 33 W	PLOT 82 TRT 34 W	PLOT 83 TRT 35 W	PLOT 84 TRT 36 W
PLOT 80 TRT 32 W	PLOT 79 TRT 31 W	PLOT 78 TRT 30 W	PLOT 77 TRT 29 W
PLOT 73 TRT 25 W	PLOT 74 TRT 26 W	PLOT 75 TRT 27 W	PLOT 76 TRT 28 W

PLOT 97 TRT1 W	PLOT 98 TRT 2 W	PLOT 99 TRT 3 W	PLOT 100 TRT 4 W
PLOT 104 TRT 8 W	PLOT 103 TRT 7 W	PLOT 102 TRT 6 W	PLOT 101 TRT 5 W
PLOT 105 TRT9 W	PLOT 106 TRT 10 W	PLOT 107 TRT 11 W	PLOT 108 TRT 12 W
PLOT 112 TRT 16 W	PLOT 111 TRT 15 W	PLOT 110 TRT 14 W	PLOT 109 TRT 13 W
PLOT 113 TRT 17 W	PLOT 114 TRT 18 W	PLOT 115 TRT 19 W	PLOT 116 TRT 20 W
PLOT 120 TRT 24 W	PLOT 119 TRT 23 W	PLOT 118 TRT 22 W	PLOT 117 TRT 21 W

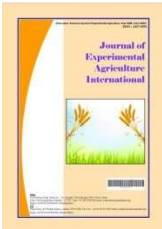
PLOT 25 TRT 25 W	PLOT 26 TRT 26 W	PLOT 27 TRT 27 W	PLOT 28 TRT 28 W
PLOT 32 TRT 32 W	PLOT 31 TRT 31 W	PLOT 30 TRT 30 W	PLOT 29 TRT 29 W
PLOT 33 TRT 33 W	PLOT 34 TRT 34 W	PLOT 35 TRT 35 W	PLOT 36 TRT 36 W
PLOT 40 TRT 40 W	PLOT 39 TRT 39 W	PLOT 38 TRT 38 W	PLOT 37 TRT 37 W
PLOT 41 TRT 41 W	PLOT 42 TRT 42 W	PLOT 43 TRT 43 W	PLOT 44 TRT 44 W
PLOT 48 TRT 48 W	PLOT 47 TRT47 W	PLOT 46 TRT 46 W	PLOT 45 TRT 45 W

PLOT 72 TRT 24 W	PLOT 71 TRT 23 W	PLOT 70 TRT 22 W	PLOT 69 TRT 21 W
PLOT 65 TRT 17 W	PLOT 66 TRT 18 W	PLOT 67 TRT 19 W	PLOT 68 TRT 20 W
PLOT 64 TRT 16 W	PLOT 63 TRT 15 W	PLOT 62 TRT 14 W	PLOT 61 TRT 13 W
PLOT 57 TRT 9 DOL	PLOT 58 TRT 10 W	PLOT 59 TRT 11 W	PLOT 60 TRT 12 W
PLOT 56 TRT 8 W	PLOT 55 TRT 7 W	PLOT 54 TRT 6 W	PLOT 53 TRT 5 W
PLOT 49 TRT 1 W	PLOT 50 TRT 2 W	PLOT 51 TRT 3 W	PLOT 52 TRT 4 W

PLOT 121 TRT 25 W	PLOT 122 TRT 26 W	PLOT 123 TRT 27 W	PLOT 124 TRT 28 W
PLOT 128 TRT 32 W	PLOT 127 TRT 31 W	PLOT 126 TRT 30 W	PLOT 125 TRT 29 W
PLOT 129 TRT 33 W	PLOT 130 TRT 34 W	PLOT 131 TRT 35 W	PLOT 132 TRT 36 W
PLOT 136 TRT 40 W	PLOT 135 TRT 39 W	PLOT 134 TRT 38 W	PLOT 133 TRT 37 W
PLOT 137 TRT 41 W	PLOT 138 TRT 42 W	PLOT 139 TRT 43 W	PLOT 140 TRT 44 W
PLOT 144 TRT 48 W	PLOT 143 TRT 47 W	PLOT 142 TRT 46 W	PLOT 141 TRT 45 W

Appendix X: List of publications

1. Ooro, P.A., Birech, R.J., Malinga, J.N. and Thuranira, E. (2021). Effect of legumes on Nitrogen Use Efficiency of Wheat in a short term Crop Rotation in Njoro Sub – County. Journal of Experimental Agriculture International, 43(3): 1 – 15, 2021; Article No. JEAI 68400. DOI: 10.9734/JEAI/2021/v43i330652.
2. Ooro, P.A., R. J. Birech, J. N. Malinga, E. Thuranira, C. Digo and R. Taiy. (2020). Influence of Crop Rotation and Soil Fertility Management Strategies on Water Use Efficiency of Wheat in a Changing Climate in Njoro Sub-County in Kenya*JEAI, 42(8): 59-76, 2020; Article no.JEAI.60830.* DOI: 10.9734/JEAI/2020/v42i830572.
3. Ooro, P., Birech, R. and Malinga, J.N. (2019). Enhancing Of Nitrogen Use Efficiency And Its Associated Attributes Through Short Term Crop Rotation For Increased Wheat Productivity In Kenya. GSJ Vol. 7, Issue 8, August 2019, Online: ISSN 2320-9186 www.globalscientificjournal.com.
4. Ooro, P.A., Birech, R., Malinga, J. N., Freyer, B. and Asch, F. (2018). Climate Smart. Agriculture Through Cropping Sequence to Enhance Nutrient Use Efficiency And Its Associated Attributes Of Wheat For Food Security. Proceedings of the 12th Egerton University International Conference, held on the 27th – 29th March, 2018, at FEDCOS Complex, Njoro Campus, Kenya, 21 – 27pp.
5. Patrick Awuor Ooro, Rhoda Birech, Joyce Maling'a, Jörn Germer, Folkard Asch, Bernhard Freyer, Rael Taiy. (2015). Effect of Pre-Crop on Growth and Yield of Potato in Kenya. Proceedings of Tropentag 2015, held on 16th – 18th September, 2015 at the University of Humboldot, in Berlin, Germany.
6. Patrick Awuor Ooro, Rhoda Birech, Joyce Malinga, Jörn Germer, Bernhard Freyer, Kibet Ngetich and Rael Taiy. (2014). Influence of Water Harvesting and Soil Fertility Management on the Performance of Wheat in Kenya. Proceedings of Tropentag 2014, held on 17th – 19th September, 2014 at Czech University of Life Sciences, in Prague, Czech Republic.



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Influence of Crop Rotation and Soil FertilityManagement Strategies on Water Use Efficiency ofWheat in a Changing Climate in Njoro Sub-County in Kenya

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Authors' contributions

This work was part of a PhD thesis. Author PAO was the student and he designed the study, assistedby authors RT, CD and ET managed the experiment, collected all the data and conducted statistical analysis. He also wrote the protocol and the first draft of the manuscript. Author RJB was the principalsupervisor while author JNM was the second supervisor. Besides supervision, they managed the literature searches. All the authors read and approved the final manuscript.

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ABSTRACT

Aims: The study determined the effect of soil fertility management (inorganic and organic N sources) and short term crop rotation (cereal – legumes cropping systems) on water use efficiency of wheat in high potential areas.

Study Design: A randomized complete block design was used with split-split-plot arrangement replicated three times. Three factors evaluated included water harvesting (WH), crop rotation (CR) and soil fertility management (SFM). The data obtained were subjected to an analysis of variance (ANOVA) using Genstat statistical package while the mean separation was performed using least significance differences (*P* =.05).

Place and Duration of Study: The trial was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) fields based in Njoro for three years between 2014 and 2016 during rainy seasons.

Methodology: Water harvesting was evaluated at consisted of flat beds (WH1) and tied ridges (WH2), crop rotation was tested at four levels comprising of Wheat- Dolichos lablab (*Lablab purpureum*)-Wheat- *L. purpureum* (CR1); Wheat-Greenpea (*P. sativum)* –Wheat (*Triticum aestivum* L)- *P. sativum* (CR2); *T. aestivum* L-potato- *P. sativum* –Potato (*Solanum tuberosum*) (CR3); and Wheat-Wheat-Wheat-Wheat) (CR4). Six different soil fertility management (SFM) strategies evaluated included SFM1 = untreated control; SFM2 = Farm Yard Manure at 5 t ha^{-1}; SFM3 = Green manure (*L.eucaena triachandra*) at 2.5 mt ha^{-1}; SFM4 = Calcium Ammonium Nitrate (CAN) at 25 kg N ha^{-1}; SFM5 = Calcuim Ammonium Nitrate at 50 kg N ha^{-1}; and SFM6 = Ammonium Nitrate (CAN) at 75 kg N ha^{-1}. The Water harvesting (WH) and SFM were fixed on the same plot at the form and rate for the entire period of the study while crops were rotated between seasons. Water use efficiency was derived as a ratio of water use and grain yield and biomass.

Results: Results revealed significant (*P* =.05) effect of crop rotation and soil fertility management on water use efficiency. However, water harvesting did not influence. While interaction of CR and SFM significantly (*P* =.05) influenced WUE and grain yield. Significant influence was also observed on WUE due to an interaction between WH and SFM. *Dolichos* lablab (*L. purpureum)* and green pea as pre-crops resulted in higher yield than when potato was the pre-crop and continuous wheat. Use of inorganic N fertilizer with *L. purpureum* as a pre-crop resulted in higher grain yield than all other soil fertility management strategies evaluated. In conclusion, the use of green pea as a pre-crop during the short rain followed by wheat in long rains is a beneficial crop rotation systems and a climate smart strategy. In addition, organic N sources should be recommended for sustainable wheat production because it will positively influence the accumulation and slow release of soil moisture for increased water use efficiency.

Keywords: Water use efficiency; water harvesting; tied ridges; soil fertility management; crop rotation.

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Effect of Legumes on Nitrogen Use Efficiency ofWheat in a Short Term Crop Rotation in Njoro Sub-County

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The study determined the effect of legumes in short term crop rotation (cereal – legumes cropping systems) on nitrogen use efficiency of wheat.

Study Design: A randomized complete block design (RCBD) was used in a split-split-plot arrangement replicated three times. Three factors evaluated included water harvesting (WH), crop rotation (CR) and soil fertility management (SFM). The data obtained were subjected to an analysis of variance (ANOVA) using Genstat statistical package while the mean separation was performed using least significance differences (*P* =.05).

Place and Duration of Study: The trial was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) fields based in Njoro for three years between 2014 and 2016 during rainy seasons.

Methodology: The treatments consisted of four pre-crops in the rotation systems (CR1 = Dolichos lablab (*L. purpureus)* as a pre-crop; CR2 = Green pea (*Pisum sativum)* as a pre-crop; potato (*Solanum tuberosum*) as a pre-crop; and CR4 = continuous wheat (*Triticum aestivum*), two water harvesting (WH) strategies (WH = flat beds; and WH= tied ridges) and six soil fertility management (SFM) strategies (SFM1 = untreated control; SFM2 = FYM at 5 t ha^{-1}; SFM3 = Green manure (*Leucaena trichandra*) at 2.5 t ha^{-1}; SFM4 = inorganic source at 25 kg N ha^{-1}; SFM5 = inorganic source at 50 kg N ha^{-1}; and SFM6 = Inorganic source at 75 kg N $ha^{-1)}$..

Results: The results revealed that the value of NUE significantly (p < 0.001) increased when *P. sativum* and *L. purpureus* preceded wheat in the short term crop rotation system. The value of NUE increased by 39% and 44%, when wheat was preceded *L. purpureus* and *P. sativum,* respectively, relative to *S. tuberosum*. Under continuous wheat, NUE value was increased by 54.17% relative to potato as a pre-crop. Overall, the contribution of legumes (*L. purpureus and P. sativum*) as precursor crops was greater than those observed with potato and wheat as pre-crops.

Keywords: Triticum aestivum; Pisum sativum; Leuceana trichandra; Lablab purpureus.

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ENHANCING OF NITROGEN USE EFFICIENCY AND ITS ASSOCIATED ATTRIBUTES THROUGH SHORTTERM CROP ROTATION FOR INCREASED WHEAT PRODUCTIVITY IN KENYA

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ABSTRACT

Kenya's agriculture is about 98% rainfed hence sensitive to climate change. Therefore climate smart agriculture (CSA) should be considered to help farmers mitigate against the impacts of climate change. In view of this, a three year study was conducted at the Kenya Agricultural and Livestock Research Organization (KALRO) in Njoro for three years mainly to quantify the effect of crop rotation on water use efficiency (WUE); nutrient use efficiency (NUE) and its associated components of wheat and potato in a cereal- potato cropping system. The trial consisted of three factors including (1) water harvesting (WH=No ridge and Tie ridge), (2) Crop rotation (CR) (Wheat-Dolichos-Wheat-Dolichos; Wheat-Greenpea-Wheat-Greenpea; Wheat-potato-Greenpea-Potato; Wheat-Wheat-Wheat-Wheat); and (3) Soil Fertility Management (SFM) = including four treatments such as untreated control; Calcium Ammonium Nitrate (CAN) at 25, 50 and 75 kg P_2O_5 ha^{-1}; Farm yard manure (FYM) at 5 t ha^{-1}, and Green manure (*Leucaena triachandra*) at 2.5 mt ha^{-1}) for three seasons. The treatments were laid out in a randomized complete block design (RCBD) with split-split arrangement with three replications. Data was subjected to an analysis of variance (ANOVA) using SAS statistical package was performed. The result showed a significantly ($P \leq 0.05$) greater influence on both water (WUE) and nitrogen use efficiency (NUE) in a situation where wheat was preceded by leguminous crop (Greenpea) than the other two crop rotation systems. Organic sources of nutrients also resulted in a positive influence on the WUE and NUE of both wheat and potato however, the influence was greater in potato than wheat. In conclusion it was confirmed that cereals grown after legumes had a positive influence on NUE and its associated components. This manifested the significant contributions of the study to the CSA concept because the reliance on crop of cereals (wheat) with legumes and the use of organic sources of fertility in short cropping cycle would help to mitigate against the impacts of climate change.

Key words: Cropping systems; water use efficiency, nitrogen use efficiency present in alphabetical order


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