IMPACT OF WATER HARVESTING TECHNIQUES AND NUTRIENT MANAGEMENT OPTIONS ON THE YIELD OF PEARL MILLET IN THE SAHELIAN ZONE OF MALI

BY

BEJAME COULIBALY

MSc. PLANT BREEDING NOVEMBER, 2015

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A Thesis submitted to the Department of Crop and Soil Sciences, Faculty of Agriculture, Kwame Nkrumah University of Science and Technology, Kumasi, in partial fulfilment of the requirements for the award of a degree of

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BY

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DEDICATION

This thesis is dedicated to my mum Haoua Dembele, my wife Jokebed Sogoba, my son Pascal Joel Coulibaly and my daughter Sara Coulibaly

DECLARATION

I hereby declare that this thesis is my own work, and that it contains no material previously published by another person nor material which has been accepted for the award of any other Degree of the University, except where due acknowledgment has been made in the text.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

LIST OF ABBREVIATIONS

Acronym	Meaning
AE	Agronomic efficiency
AGRA	Alliance for Green Revolution in Africa
Av. P	Available phosphorus
CEC	Cation exchange capacity
CIMMYT	International Centre for the Improvement of Maize and Wheat
cm	Centimeter
$cmol_c$	Centimole charge
DAP	Diammonium Phosphate
DAS	Days after sowing
DNA	Direction National de l'Agriculture

FAO	Food and Agriculture Organisation of the United Nations
FCFA	Franc des Colonies Françaises d'Afrique
FYM	Farm yard manure
GRDC	Research and Development Corporation
ha	Hectare
HI	Harvest index
IER	Institut d'd'Economie Rurale
kg	Kilogramme
KNUST	Kwame Nkrumah University of Science and Technology
L	Liter
Labo-SEP	Laboratoire Sol Eau Plante
Lsd	Least significant difference
Mg	Magnesium
mg	Miligramme
MRP	Minjingu Rock Phosphate
NFB	Net Farm Benefit
NUE	Nutrient use efficiency
SOC	Soil organic carbon
RWUE	Rainwater use efficiency
SRA	Station de Recherche Agronomique
TDM	Total dry matter
VCR	Value Cost Ratio

ABSTRACT

Low inherent soil fertility as well as inappropriate water and nutrient management practices are the major constraints to pearl millet productivity in the Sahelian zone of Mali. In order to increase the productivity of millet in Mali, the current research was conducted at the Agricultural Research Station of Cinzana, Mali during the rainy seasons of 2013 and 2014. The objectives of the study were to determine the effect of water harvesting techniques and nutrient management options on: (i) growth and yield of pearl millet, (ii) soil moisture content and rainwater use efficiency, (iii) partial N and P balances and nutrient use efficiency. The cost effectiveness of water harvesting techniques and nutrient management options were also ascertained. The water harvesting techniques evaluated were zai, tied ridge and conventional tillage (control).

Cattle manure was applied at 0 and 2500 kg ha^{-1}, while mineral fertilizer was applied at 0, 20.5 kg N: 23 kg P_2O_5 ha^{-1} and 41 kg N: 46 kg P_2O_5 ha^{-1}. Experimental design was split – plot with randomized complete block design.

The results showed that the pearl millet grain yield increased from 47 to 67 % under zai, 31.37 to 53.00 % under tied ridge as related to conventional tillage. Manure application improved pearl millet grain yield by 29 to 45 % over the control. The mineral fertilizer application increased pearl millet grain yield by 34 to 54 % compared to the control. The combined application of 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} increased grain yield from 1370 kg ha^{-1} in 2013 to 1716 kg ha^{-1} in 2014, while the increases in the control were 433 kg ha^{-1} in 2013 to 846 kg ha^{-1} in 2014. Straw yield of pearl millet increased by 30 to 41 % under zai and 25 to 37 % under tied ridge as compared to the conventional tillage. Combined application of manure and mineral fertilizer improved straw yield on average by 23.37 to 35.00 % and 18.80 to 27.17 %, respectively over the control. Manure had a higher (27.77 %) harvest index than the control (23.85 %) in 2013 cropping season. The mineral fertilizer application recorded the highest value of harvest index (28.10 %) compared to the control (22.01 %). Application of manure and mineral fertilizer improved N and P agronomic efficiencies. Soil moisture content significantly improved with water harvesting techniques. Zai recorded the highest value (52.06 mm) of soil moisture stored followed by tied ridge with 47.16 mm and the lowest value (39.48 mm) obtained under conventional tillage within the 20 – 40 cm depth at 45 days after sowing. Manure application increased soil moisture stored in both depths as compared to the control. The rainwater use efficiency recorded under zai and tied ridge were 3.45 and 3.17 kg grain mm^{-1}, respectively as compared to the 2.06 kg grain mm^{-1} under conventional tillage.

Manure application increased RWUE by 33.00 % as compared to the control, while mineral fertilizer improved RWUE by 31.64 to 35.00 % over the control. In the 2014 cropping season, nitrogen uptake by grain was 26.00 and 52.75 % higher under tied ridge and zai pit, respectively than conventional tillage. In the 2014 cropping season, phosphorus uptake by grain was 57 and 71 % higher under tied ridge and zai pit, respectively than the control. In both years, the application of manure at 2500 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} led to positive partial P and N balances. The most cost effective water harvesting technique was the tied ridge, while the application of mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} with 2500 kg ha^{-1} of manure gave the highest returns on investment. Consequently, the use of tied ridge and mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} with 2500 kg ha^{-1} of manure could be an appropriate option for improving millet productivity in Mali.

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CHAPTER ONE

1.0 INTRODUCTION

Food insecurity and soil fertility depletion across much of sub-Saharan Africa in recent decades have led to the pursuit of alternative nutrient management strategies for restoring degraded soils and improving crop yields (Sanchez, 2002). Most soils in Mali have low fertility status mainly as a result of nutrient mining. It is estimated that about 22.5 kg N ha^{-1}, 5.9 kg P ha^{-1} and 27.3 kg K ha^{-1} are lost annually from pearl millet production system (FAO, 2005).

Pearl millet (*Pennisetum glaucum* (L.)) is the most important rainfed crop in the Sahelian area of Mali. The grain yields of this cereal are low, usually below 514 kg ha^{-1} (DNA, 2011). Poor distribution and scarcity of rainfall as well as low inherent soil fertility are some of the major constraints to cereals production in Mali (Samaké, 2003). Tabo *et al.* (2007) reported that about 38 % of rainfall is lost through runoff. In rainfed fields, improvement may come from conserving rainwater in the root zone of crops, and managing the field and the crops to use water more efficiently. According to Barron (2004), improved water use with best fit soil fertility management practices are major pathways for improving crop productivity in smallholder farming systems.

The application of inorganic inputs is recognized as a convenient way for rapidly restoring nutrient deficiencies in soils. For economic reasons, smallholder farmers cannot apply the recommended rates of mineral fertilizers (Adamou *et al.*, 2007). The use of manure has, therefore, become the best way to improve soil properties and increase grain yield of cereals (Palm *et al.*, 2001), but the quantities of manure available to smallholder farmers are low (Mafongoya *et al.*, 2007). To address the constraints for using manure and mineral fertilizer, Buerkert *et al.* (2001) proposed the combined application of mineral and organic input as an appropriate strategy to improve soil fertility and increase crop yields.

In Mali, soil and water conservation technologies have not been adopted by smallholder farmers (Kanté, 2001). Key reasons for the low adoption rates include lack of labour, high cost and ignorance of technologies (Shetty *et al.*, 1998). Many studies have evaluated the effect of water harvesting techniques such as tied ridge and zai on the grain yield of cereals (Kouyaté *et al.*, 2012; Kassogue *et al.*, 1996; Wedum *et al.*, 1996). Yet, availability of water alone cannot improve crop yield sustainably (Zougmoré *et la.*, 2003b).

Consequently, evaluation of soil water harvesting techniques should be carried out together with nutrient inputs. Such studies are, however, rare in the Sahelian agroecological zone of Mali. Considering the low inherent soil fertility of the soil in the Sahelian zone and the arid nature of climate, it is imperative for the smallholder millet farmers to combine manure, inorganic fertilizers and appropriate water harvesting techniques to increase grain yield.

The main objective of this study was to increase grain yield of millet on smallholder farms, through the use of efficient nutrient management and water harvesting strategies. Working on the main hypothesis that, the use of improved soil water harvesting and nutrient management options lead to increases in pearl millet yield.

The specific objectives were to assess the impact of different soil amendments and water harvesting techniques on:

i. growth and yield of pearl millet; ii. soil moisture content and rainwater use efficiency ; iii. nutrient use efficiency and partial N and P balances; and iv. cost effectiveness .

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Contraints of pearl millet production in the Sahelian zone of Mali

In the sahelian zone of West Africa, land degradation through water and wind erosion, nutrient mining and extreme utilization of the vegetation, lack of organic matter and mineral fertilizer constitute the major concern (Bationo *et al.*, 1998). Sivakumar *et al.* (1995) indicated that 65 % of the African agricultural land, 31 % of permanent grazing land, and 19 % of forest have already been degraded. Furthermore, land degradation in combination with the high temperature in the early rainy season, causes high seedling mortality, poor crop establishment and yield losses. Scherr (1999) provided reviews of land productivity in Africa and estimated crop production losses due to land degradation at more than 20 % during the last forty years. Kieft *et al.* (1994) reported that the bare soil in Mali increased from 4 % in 1952 to 26 % in 1975.

Population increase was accompanied by a strong reduction of fallow, a decrease in soil fertility, increasing erosion, a drop in agricultural production and a strong expansion of cultivated lands over soils marginal to agriculture (Schlecht and Buerkert, 2004). The area of cultivated land increased much faster than the population, which is an indicator of agriculture intensification (Bagayoko *et al.*, 2011). The extension system has not been able to offer effective resource enhancing technologies acceptable to resource-poor farmers (Kaboré and Reij, 2004).

Many initiatives have been undertaken in combating soil degradation. Various practices including (1) parkland trees associated with crops, (2) coppicing trees, (3) green manuring, (4) mulching, (5) crop rotation and intercropping, and (6) traditional soil and water conservation have been tested (Bayala *et al.*, 2012). The strategies for improving the efficiency of water conservation techniques could be the combined practice of soil fertility management (application of mineral and organic fertilizers) and water harvesting techniques such as, stone bunds, contour ridge, terracing, tied ridges or vegetation cover through the mulching. Researchers working with the producers care more to seek ways and means to develop participatory techniques to mitigate the effects of rainfall variability on agricultural production.

Pearl millet (*Pennisetum glaucum* (L.)) is the most important rainfed crop in the Sahelian area of Mali. It is the cereal mostly consumed by smallholder farmers and cultivated on about 30 % (1,639,875 ha) of the total cropping land under cereals
(4,285,662 ha). The national millet production was 1,666,085 Mg year^{-1} (DNA, 2011). According to Samaké (2003), the main constraints to millet production were the low state budgets for investment at the regional and district levels that lead to high prices of inputs and low prices of outputs at the smallholder farmers level.

2.2 Some soil management practices to sustain crop production in the sahel

Several techniques are available in the sahelian zone to ensure soil conservation in agriculture. The most important management techniques used to restore soil fertility and to rehabilitate degraded soils include fallow, mulching, crop rotation, intercropping, half - moon, stone line, land diguette, zai, tied ridge, organic and mineral fertilizers application. This study focuses on the effect of tied ridge and zai combined with organic and mineral fertilizer application on growth and yield of pearl millet and selected soil chemical and physical properties.

2.2.1 Organic amendment and mineral fertilizer applications

Blanket recommendations of mineral fertilizers (DAP and NPK) and manure for cereal production in Mali were formulated 20 years ago. 100 kg ha^{-1} of DAP (18 – 46 – 0 NPK) or (15 – 15 – 15 NPK) were applied together with 50 - 100 kg ha^{-1} urea. An annual application of 5000 kg ha^{-1} of organic manure was also recommended (Kieft *et al.*, 1994). These recommendations, for economic reasons (Adamou *et al.*, 2007; Spielman *et al.*, 2010), are not applied by smallholder farmers. As a result, low yields of sorghum and millet (about 400 - 1000 kg ha^{-1}) are obtained by smallholder farmers (Van der Pol and Traore, 1993; Stoorvogel *et al.*, 1996; Dembélé *et al.*, 1998). Organic manure influences nutrient availability by releasing nutrients, through mineralization – immobilization process, it is also acts as energy source for microbial activities and by reducing P sorption of the soil (Palm *et al.*, 1997). Because of scarcity of organic manure, Sawadogo *et al.* (2008) demonstrated that the application of mineral and organic fertilizers together with water harvesting is a most credible option for meeting the growing demand for food without increasing dependence on foreign aid. In Niger, tests conducted by farmers showed that millet yields could be increased by more than 250 % by the use of fertilizers (Bationo and Mokwunye, 1991b).

Combined application of organic and mineral nutrient sources may lead to synergistic, antagonistic or additive effects on crop production (FAO, 2003). Where an interaction is synergistic (positive), the combined effect of the nutrient sources on crop production is greater than the sum of their individual effects used singly. In an antagonistic (negative) interaction, their combined impact on crop production is lower than the sum of their individual effects. An additive (no interaction) effect is found where the combined effect of nutrient source on crop production is directly equivalent to the sum of their individual effects when applied separately (Opoku, 2011). Considering the diverse meanings of the word ‘interaction”, Palm *et al.* (1997) proposed the term ‘added benefit (or disadvantages)’ as a better phrase for interactive effects. Also, some studies have shown that the rational management of mineral and organic fertilizer increases yields of crops and maintains sustainable soil fertility (Adamou *et al.*, 2007). Njeru *et al.* (2015) reported that the combination of 5 Mg of cattle manure and 40 kg N ha^{-1} increase maize grain yield. The same authors confirm the efficiency of the combination of organic and mineral fertilizer. Mugwe *et al.* (2009a) reported that the use of cattle manure contributing 30 kg N ha^{-1} in combination with mineral fertilizer (30 kg N ha^{-1}) produced higher maize yields than with simple mineral fertilizer (60 kg N ha^{-1}).

Shahandeh *et al.* (2004) found that application of Tilemsi rock phosphate (TRP) increased millet yield by up to 89 % compared to the control. The augmentation in millet yield was attributed to increase in the plant available P and Ca. Bollan *et al.* (1990) reported that incorporation of rock phosphate ensures a steady supply of P over a long period and also provides a high rooting density to crops. The positive effect of rock phosphate on soil properties with amendments and consequently on crop growth and grain yield has been reported by several authors. Okande *et al.* (2011) showed that application of Ogun rock phosphate (ORP) as a source of P, with or without amendments improved the growth and seed yield of kenaf. However, amending the ORP with various organic wastes and urea gave comparable growth and seed yields with NPK application. High grade of rock phosphate mixed with sulphate of ammonia performed better than DAP at the same rate of P (60 kg ha^{-1} of P) in pot experiment with *Phaseolus vulgaris* as test crop. The average biomass recorded after 25 days of sowing was 6.08 g and 3.86 g, respectively for rock phosphate and DAP (Raguram and Ramachandra, 2014).

2.2.2 Location and characteristics of Tilemsi rock phosphate deposits in Mali

Deposits of rock phosphate in Mali are known since 1930. The rock phosphate deposits are found in the north eastern part of Mali, in the Tilemsi valley. Presently, a number of deposits are known and grouped under the name of Bourem including the Tamaguilelt, Chanomaguel, Tin-hina, Sagariguita (Samit) deposits. The best-studied area of phosphate rocks in the Tilemsi area is that of Tamaguilelt (17° 40' N; 0° 15' E). Here, the unconsolidated phosphate sediments consist mainly of fish and reptile bone debris as well as coprolites (Van Straaten, 2002). Approximately, 10 million Mg at the Tamaguilelt deposit are located beneath 15 m of overburden (Sustrac, 1986).

The reserve was estimated to be 20 million Mg with an average P_2O_5 content of 27–28 percent. Tilemsi rock phosphate (TRP) is a medium reactive rock suitable for direct application. TPR has solubility greater than 40 % in 2 % formic acid (Zapata and Roy, 2004). This reactivity is attributable to a relatively high degree of carbonate substitution for phosphate in the rock minerals. The entire production of TRP is used within the country.

The mineralogical composition of mineral varies from site to site. In-depth studies have indicated that the main components of the TRP are phosphorus (25 – 32 %) and calcium (35 – 45 %) (Henao and Baanante, 1999). Detailed mineralogical investigations have identified the phosphate mineral as francolite with crystallographic unit-cell “a” value of

9.331 Â indicating a relatively highly reactive rock phosphate. Indeed, the neutral ammonium citrate solubility of Tilemsi RP is high (42 % P_2O_5) (Debrah, 2000; Somado *et al.*, 2003) making it suitable for direct application as phosphate fertilizer.

2.2.3 Water harvesting techniques

Water harvesting techniques are commonly successful at the farm level because they are capital extensive and labour intensive, and they can be carried out in dry seasons when other agricultural activities are minimal. These techniques are popular because physical results are immediately visible in the form of yield increases and because they assist families to meet their food security needs by increased production of staples, and they help to decrease the risk of crop failure (FAO, 2001). Optimizing soil water use is concerned with the whole 'water path' from the moment rain or irrigation water reaches the soil surface until the crop productively transpires it (Fatondji, 2002). At all stages it is essential to minimize the diversion of water into unproductive side-paths and to ensure that its utilization by the crop is as efficient as possible. Among the techniques used in collecting rainwater and improving its infiltration are the half – moon and stone bund with a large base up to 1 m (Fatondji, 2002). These techniques increase cereal grain yields in low rainfall condition. Zai and tied ridge facilitate the concentration of water and nutrients in rooting zone of crop for improved yields (Fatondji, 2002; Roose *et al.*, 1993; Motsi *et al.*, 2004; Mupangwa *et al.*, 2006).

2.2.3.1 Zai pit technique for land rehabilitation

The zai or pit of planting or "pocket of water" is a traditional management practice used in the Dogon plateau (Mali) and which is adapted in the Sahelian zone (Kassogue *et al.*, 1996). Traditionally, zai pits measure 20 - 40 cm in diameter and 10 - 15 cm in depth and are dug with a hoe. Generally, handful (0.3 kg) of animal manure or compost is applied per pit (Zougmoré *et al.*, 2004). Farmers use this technique to combat land degradation and to restore soil fertility (Fatondji, 2002). Zai is not recommended on sandy lands and lowlands. On sandy soils, the holes are not stable and risk of flooding is high. The zai technique is particularly relevant in areas characterized by intensive use of land and allows recovering additional acreage (Roose *et al.*, 1993). In Niger, Fatondji (2002) found that, zai had a good potential to increase agronomic efficiency, nutrient use efficiency and increased pearl millet grain yield. Roose *et al.* (1993) found that zai technique increased soil biological activities, which involved the colonization of the field by several varieties of grass. The same study demonstrated that the zai pit technique with manure increased pearl millet grain yield to 1157 kg ha^{-1} compared to flat planting with manure that yielded 705 kg ha^{-1}. In Burkina, Zougmoré *et al.* (2004) reported that zai pit reduces runoff by increasing infiltration through breaking the surface crust and creating and enhancing depressional water storage as well as improving and reducing erosion. The increased yields varied from 300 to 400 kg ha^{-1} by the zai system in degraded land (Sawadogo *et al.*, 2008). Kaboré and Reij (2004) indicated that an additional dose of inorganic fertilizer, in combination with the zai pits and manure, increased yields by 640 kg ha^{-1} compared to the control plots. In Mali, Wedum *et al.* (1996) reported that zai with manure increased sorghum grain yield by 212 %.

In Mali, zai technique studies were limited to its effect on grain yield of sorghum and pearl millet at the farm level (Wedum *et al.*, 1996; Kassogue *et al.*, 1996). A major challenge associated with the zai pit technique was its high labour of 60 man days required to dig the number of zai pits needed on a sorghum field (Kaboré and Reij, 2004; Zougmoré *et al.*, 2003b).

2.2.3.2 Tied ridge as a water harvesting technique

Tied ridge, in which ridges are connected with cross-ties over the intervening furrows, is an improvement over the traditional ridge-furrow system. The system results in a series of rectangular depressions which impound water during rain. Under the tied ridging practice the soil is left undisturbed from harvest to planting except for a strip up to onethird of the row width (Serme, 2014). Ridges (30 cm high) and ties (cross ridges, 20 cm high) are constructed to create a series of basins for storing water. The spacing of the ridges is 90 cm and the cross ridges are made at 2.5 m interval using a hoe to prevent flow of runoff water (Miriti *et al.*, 2007). Ridges are reshaped during the growing period of the crop. Tied ridging reduces surface bulk density, maintains soil fertility by reducing losses of soil nutrients in surface runoff and improves soil water retention and available water holding capacity (Hulugalle, 1990).

In Mali, tied ridge increased grain yields of sorghum in rotation with legumes by 10 % compared to simple ridging under low average rainfall in the sahelian zone (Kouyaté *et al.*, 2012). Sorghum grain yield increased by 30 to 50 % in farmers fields practising tied ridging with animal drawn equipment in the areas of Koutiala and Tominian in Mali (DRSPR, 1990). Miriti *et al.* (2007) reported that tied ridging, in combination with integrated nutrient management, had the potential to improve crop production in semiarid zone of Kenya. Chepkemoi (2014) reported that intercrop and crop rotation of sorghum under tied ridges with application of Minjingu Rock Phosphate (MRP) and Farm Yard manure (FYM) is a viable technology for increased soil moisture, nutrients, and crop yield. In Nigeria, Chiroma *et al.* (2008) indicated that pearl millet grain yield exceeded 35 % compared to the flat planting. In Ethiopia, Belay *et al.* (1998) showed that tied ridge, combined with crop residue and mineral fertilizer, increased maize grain yield by 20 %. Yoseph and Gebre (2015) indicated that grain yield obtained from tied ridge (3625 kg ha^{-1}) was higher by 55.72 % compared to farmers' practice (1605 kg ha^{-1}).

The review of the literature has shown that in Mali, no study has been undertaken on combined organic and mineral fertilizer and tied ridge to evaluate pearl millet yield, to understand nutrients use efficiencies and to compare this technique to zai, as an economically viable option of appeal to smallholder farmers.

2.2.3.3 Conventional tillage, the common traditional practice by farmers

Blanco-Canqui and Lal (2008) defined conventional tillage as any tillage system that inverts soil and alters the natural soil structure. Typically, it includes ploughing and harrowing to produce fine seedbed and removal of most of the plant residues from the previous crop (Ouattara, 1994). Ploughing is done with a mouldboard or disc-plough which inverts the soil to a depth of 10 – 20 cm. During the operation, the soils are cut, inverted and pulverized, burying most of the residues underneath (Luchsinger *et al.*, 1979). With pulverized soil on the surface and compaction below, a lot of soil is washed away with the first rains (Kaihura *et al.*, 1998). In the short-term, conventional tillage reduces runoff and soil compaction, but this effect is lost as soon as the first rainfall occurs producing a crusting effect (Rao *et al.*, 1998). According to Lawrence *et al.* (1994), water harvesting techniques resulted in higher wheat grain yield than conventional tillage in a four year study in a semi-arid environment in Australia. Serme (2014) reported that Tied-ridging with Compost + NPK + Urea increased sorghum grain yield by 28% as compared with conventional tillage with the same fertility management options. Mullins *et al*. (1998) reported that conventional tillage (chisel ploughing) resulted in yield losses: 14 % in dry matter yield and 30 % in grain yield, but this is contrary to the findings of Khan *et al*. (2009) who reported biomass and grain yield, grains per cob and thousand grain weight to be highest in the case of conventional tillage. Sarauskis *et al.* (2009) indicated that conventional tillage reduced rainwater retention in the potential root zone as compared with conservation tillage.

2.2.3.4 Effect of water harvesting techniques and nutrient management options on yield of pearl millet

The growth and yield of cereals have been affected by water harvesting techniques (Zougmoré *et al.*, 2003b; Kaboré and Reij, 2004). Fatondji (2002) reported that zai, combined with manure application, increased pearl millet grain yield at 1100 kg ha^{-1} compared to the control (flat) which was 705 kg ha^{-1}.

In Mali, Kouyaté *et al.* (2012) reported that tied ridge in rotation or intercropping recorded higher sorghum grain yield of 1810 kg ha^{-1} than ripping of 1640 kg ha^{-1}. The same study showed that under tied ridge with sorghum monoculture system, the yield decreased from

1600 to 1230 kg ha^{-1}. The lower yield under the monoculture was attributed to water constraint. Miriti *et al.* (2007) observed that tied ridge in combination with integrated nutrient management had the potential to improve crop production in semi-arid eastern Kenya. In fact, farmers in the sahelian area are not practising adapted water harvesting techniques that enhance soil water and the availability of N, P and K nutrients added as fertilizer to soils (Zougmoré *et al.*, 2004).

The combination of water harvesting techniques and nutrient management options is to make available both water and nutrients to crop. In Kenya, Njeru *et al.* (2015) reported that integration of organic and inorganic inputs under various water harvesting technologies could be considered as an alternative option towards food security under climate change for semi-arid areas. Combining soil and water conservation techniques with organic nutrient sources improved the chemical characteristics and productivity of the soil (Zougmoré *et al.*, 2004; Zougmoré *et al.*, 2003b; Kaboré and Reij, 2004). Gichangi *et al.* (2007) showed that farmers need to augment the limited quantities of farmyard manure available on smallholder farms with inorganic fertilizers in addition to appropriate water harvesting techniques for increasing the yields of maize and beans. Also, the half - moon with compost or animal manure application generated a greater sorghum yield than when used with the mineral fertilizer; and in the control plot Zougmoré *et al.* (2004) and Zougmoré *et al*. (2003b) showed that water conservation without the addition of nutrients does not bring a significant increase in crop yield, particularly in years when rainfall distribution is good.

2.3 Effect of water harvesting techniques on soil moisture content

Soil moisture measurements are frequently neglected in agronomic studies, yet improved soil moisture management is essential for sustainable water supply and food production (Shaxson and Barber, 2003). Soil moisture availability depends on factors of climatic conditions and management practices such as rainfall, soil properties, temperature regimes and soil moisture storage capacity (Rockstrom, 2003). Soil moisture is an important factor that influences seed germination, emergence and plant growth. It is very essential for root growth, so adequate moisture will improve uptake of nutrients by diffusion and root interaction. Soil moisture is also important for organic matter decomposition (which releases N, P and S) (Ketterings *et al.*, 2008). Improvement of soil moisture storage can be achieved by employing tillage practices that enhance rainwater infiltration and suppress subsequent evaporation. In order to enhance soil moisture, there is need to maintain soil surface conditions necessary for rapid infiltration and the removal of soil profile layers that restrict water percolation through sustainable tillage (Karuma *et al.*, 2012). Soil moisture conservation is one of the major advantages of zai and tied ridge crop production. In Ethiopia, Yoseph and Gebre (2015) reported that tied ridge is the best practice for moisture conservation for increased crop productivity. Tied ridge, with application of farmyard manure and Minjingu rock phosphate, has been reported to be a more efficient technique for moisture conservation (6.73 %) than the oxen ploughing (3.2 %) (Chepkemoi, 2014).

Studies to compare the effect of tied ridge, zai and conventional tillage on soil moisture concurrently are needed to estimate their moisture conservation potentials.

2.4 Rainwater use efficiency

The challenges in rainfed agriculture are compounded by erratic, highly variable rainfall patterns in space and time. The data on rainfall partitioning indicate that at least 38 % of the received rainfall is lost to runoff. The modeled results indicate that crop yield can be improved to 800 kg ha^{-1} if significant portion of rainfall lost to runoff is harvested (Tabo *et al.*, 2007). Shaxson and Barber (2003) reported insufficient soil water as a main cause of low crop output of poor nutritional quality. In rainfed fields, improvement may come from conserving rainwater in the rooting zone of crops, and also from managing the field and the crops to use this water more efficiently. In limited cases, supplementation of water collected from off-site water harvesting can be used to bridge small periods of water deficit (FAO, 2001).

Water use efficiency (WUE) is the measure of a cropping system's capacity to convert water into plant biomass or grain. It includes both the use of water stored in the soil and rainfall during the growing season (GRDC, 2009). According to GRDC (2009), increasing the amount of water stored in fallows is an important strategy in managing the risks associated with highly variable rainfall to improve water use efficiency and potential crop yields.

In Niger, Fatondji (2002) reported that zai improved water use efficiency by a factor of about 2 to 3 times compared to flat planting. In Nigeria, Chiroma *et al.* (2008) showed that water use efficiencies of open ripping and tied ridge were 23 and 33 %, respectively relative to the flat terrain.

2.5 Effect of water harvesting techniques and nutrient management options on soil chemical properties

Soil pH is one of the key indicators of soil fertility. It is an important measurement to assess the potential availability of beneficial nutrients and toxic elements to plants. The zai technique and composted manure enriched with Burkina rock phosphate has been found to improve soil pH (Sawadogo *et al.*, 2008). The pH was 5.5 - 5.8 in treatments with compost compared to the pH in the initial soil of 5.1. In Mali, Kouyaté *et al.* (2012) reported that tied ridge combined with cowpea/sorghum rotations enhanced soil pH by 8 % than the initial soil pH.

The dissolution of apatite in rock phosphate releases anions (CO_3^{2-}) and (PO_4^{3-}) that can consume H^+ ions and, thus, it can increase soil pH, depending on rock phosphate reactivity (Hellums *et al.*, 1989). They also reported that, if a rock phosphate contains a significant amount of free carbonates, it can further increase soil pH. However, although an increase in soil pH may reduce the Aluminium saturation level, it can also reduce apatite dissolution at the same time. The optimum condition would call for a soil pH that is high enough to reduce the Aluminium saturation level but still low enough for apatite dissolution to release P.

Leu (2007) reported soil organic carbon to increase farm profitability though increased yield, soil fertility, soil moisture retention and mineral fertilizer nutrient availability. In Mali, Kouyate *et al.* (2012) found that tied ridge combined with sorghum/cowpea rotation and fertilizer application improved soil organic carbon by 0.3 %.

Cation exchange capacity is used as a measure of soil fertility, nutrient retention capacity, and the capacity to protect groundwater from cation contamination. Ouédraogo *et al.* (2001)

reported that compost application increased soil cation exchange capacity from 4 to 6 $cmol_c$ kg^{-1}. Roose *et al.* (1993) indicated that zai improved the cation exchange capacity of soil. Nitrogen and phosphorus are the most important elements for plant growth. They are affected by soil moisture, organic matter, nutrient content and environmental conditions. In the sahelian zone, Adamou *et al.* (2007) found soil phosphorus to be very low (< 2 mg P kg^{-1}). Consequently, the combined application of manure or compost and rock phosphate is recommended to increase the availability of phosphorus in the soil (Hellal *et al.*, 2013). Zai has been found to improve the availability of nitrogen and phosphorus in the soil (Roose *et al.*, 1993). Zafar *et al.* (2012) indicated that combined use of inorganic P with compost resulted in a significant increase in total N (13 - 75 %) and available P (7 - 57 %).

2.6 Soil fertility management options

This section focuses on amendment effects on pearl millet growth and yield and fertility management options on nutrient uptake and use efficiency.

2.6.1 Effect of organic and mineral fertilizer application on pearl millet growth and yield

Soil amendments in the form of organic and mineral fertilizer of various kinds are primarily applied to the soil to enhance soil fertility status that would improve crop growth and yield. Mineral fertilizers such as DAP or NPK are commonly used by pearl millet farmers to increase crop yield because of the high nutrient content and rapid uptake compared to manure (Adamou *et al.*, 2007). Though mineral fertilizers might be extremely advantageous in improving crop yield, its over-application could cause deterioration in soil physical, chemical and biological properties and even result in stagnant or low crop yields. Pearl millet productivity is constrained by soil P and N availability (Bationo and Mokwunye, 1991a) in West African countries.

Mineral fertilizer application has been reported by several authors to increase pearl millet yields and sustain/improve the soil nutrient status (Bationo *et al.*, 1998; Bagayoko *et al.*, 2011; Sahrawat *et al.*, 2001; Buerkert *et al.*, 2001). Unavailability and high cost of mineral fertilizer to smallholder farmers explain its low use (Fairhurst, 2012). To resolve this problem, farmers are encouraged to use manure or its combination with mineral fertilizers.

Organic resources play a critical role in both short-term nutrient availability and longerterm maintenance of soil organic matter in most smallholder farming systems in the tropics (Palm *et al.*, 2001). The role of organic manure is to maintain soil fertility by improving soil physical, chemical and biological properties and increasing crop yield (Reeves, 1997; Qiu *et al.*, 2014). Many studies have been conducted on the response of N, P, and K fertilizer and their combination with manure on pearl millet (Adamou *et al.*, 2007; Raun and Johnson, 1999; Schlecht *et al.*, 2006; Aggarwal *et al.*, 1997).

In Niger, Fatondji (2002) reported that pearl millet grain yield increased further with the application of organic amendments. Manure application resulted in 2 - 68 times higher grain yields than no amendment and 2 - 7 times higher grain yields than millet straw incorporation to soil. According to Maman and Mason (2013), the combined application of poultry manure and mineral fertilizer enhanced cereal grain yield by 56 % and stover yield by 53 %. Several studies have shown that rotation and intercropping of pearl millet/cowpea improved stover and grain yields (Samba *et al.*, 2007; Bationo and Ntare, 2000; Reddy *et al.*, 1992). In Ethiopia, Bayu *et al.* (2006) demonstrated that inorganic fertilizer and farmyard manure increased stover and grain yield of sorghum by 8 - 21 and 14 - 21 %, respectively.

2.6.2 Influence of soil fertility management on nutrient uptake and use efficiencies

Nutrient uptake is the procedure by which plant roots absorb nutrients from soil solution. The nutrients absorbed are distributed to aerial portions of the plant (Havlin *et al.*, 2005). The uptake is influenced mainly by climatic conditions, the available quantity of nutrients in the soil and the form in which the nutrients are present in the soil (Allen and David, 2007).

Many studies have demonstrated that soil fertility management increases nutrient uptake by pearl millet (Fatondji, 2002; Yamoah *et al.*, 2003). In Niger, Fatondji (2002) found that zai improved nutrient uptake in the range of 43 - 64 % for N, 50 - 87 % for P and 58 - 66 % for K. According to Nyamangara *et al.* (2013), nitrogen uptake by maize under cattle manure and mineral nitrogen treatment was higher than the no nitrogen treatment. The mineral N was used to prevent N deficiency during the early part of the season.

Hellal *et al.* (2013) reported that farm yard manure enriched with phosphate (phosphocompost) was most effective in increasing phosphorus availability and uptake in red soil and increasing dry matter yield of maize. According to Mafongoya *et al.* (2007), integrated nutrient management increased nutrient use efficiency reduced costs and increased profitability. Nwachukwu and Ikeadigh (2012) demonstrated that maize fertilized with poultry manure had higher water use efficiency (54.6 g L^{-1}) over those fertilized with urea (48.7 g L^{-1}). They also showed that poultry manure application significantly increased maize N and P uptake compared to the control. However, there is a need to assess nutrient uptake under a combination of soil amendments with zai or tied ridge in the same environment.

2.7 Economic indicators to assess the profitability of water harvesting techniques and nutrient management options

Several tools are available to evaluate profitability of new soil technologies. Indeed, there is the need to link the agronomic efficiency to the financial profitability for the evaluation of any soil technology. The most frequently used indicators to assess the cost effectiveness of an agricultural enterprise are: the Value Cost Ratio (VCR), the Net Farm Income (NFI) and the Net Present Value (NPV), etc. The NPV is calculated as the value of outputs divided by the value of inputs with NPV greater than or equal to one being productive (Lynam and Herdt, 1989). According to Zhen and Routray (2003), the NFI is the difference between gross income of farm production and the total variable costs per unit of land area, while the VCR is the agronomic efficiency of the prices of inputs and outputs. An enterprise is considered economically profitable when the NFI is greater than zero and the VCR is greater than one.

In Kenya, Odendo *et al.* (2006) showed that combined application of 30 kg P and 2500 kg ha^{-1} of Farmyard manure per hectare gave economically viable maize grain yield response because the net benefit varied between 355 - 375 US Dollars. According to Opoku (2011), the value cost ratio (VCR) obtained from the combined application of manure and fertilizer (2.3 – 4.7) were greater than the economic viability threshold in Nyankpala.

2.8 Summary of literature review

A general of pearl millet production constrains in the Sahel particularly in Mali have been reviewed. The position of Mali, where this study was undertaken, relative to the general state of agriculture and food security in Africa, has been examined to reveal gaps which require remedial measures. Previous works and efforts in providing solutions to soil and crop productivity constraints in Mali have been extensively reviewed to serve as a basis for the choice of potential adaptive soil management technologies for the current study. This review covers, among others, the use and impacts of different soil management practices, particularly water harvesting, cattle manure and mineral fertilizers, on soil and crop productivity. Particular attention has been directed at the impacts of these practices on in-situ water harvesting and use given the peculiar circumstances of unimodal rainfall regime, limited rainy days, long dry periods and soil moisture constraints to crop production in Mali.

2.9 Knowledge gaps

- Most of the studies have evaluated the effect of water harvesting such as tied ridge and zai on the grain yield of cereals. There is lack of information on soil moisture content and nutrient uptake in pearl millet production.
- The mineral fertilizers are expensive and organic fertilizer is limited. To reduce the cost of fertilizers and manage the small amount of organic fertilizer, it was necessary to assess water harvesting techniques combined with soil amendments application and to identify the best rate of combination for small holder farmers.

- Many of the studies reviewed did not consider economic analysis of the nutrient fertilizer inputs or water harvesting techniques evaluated.

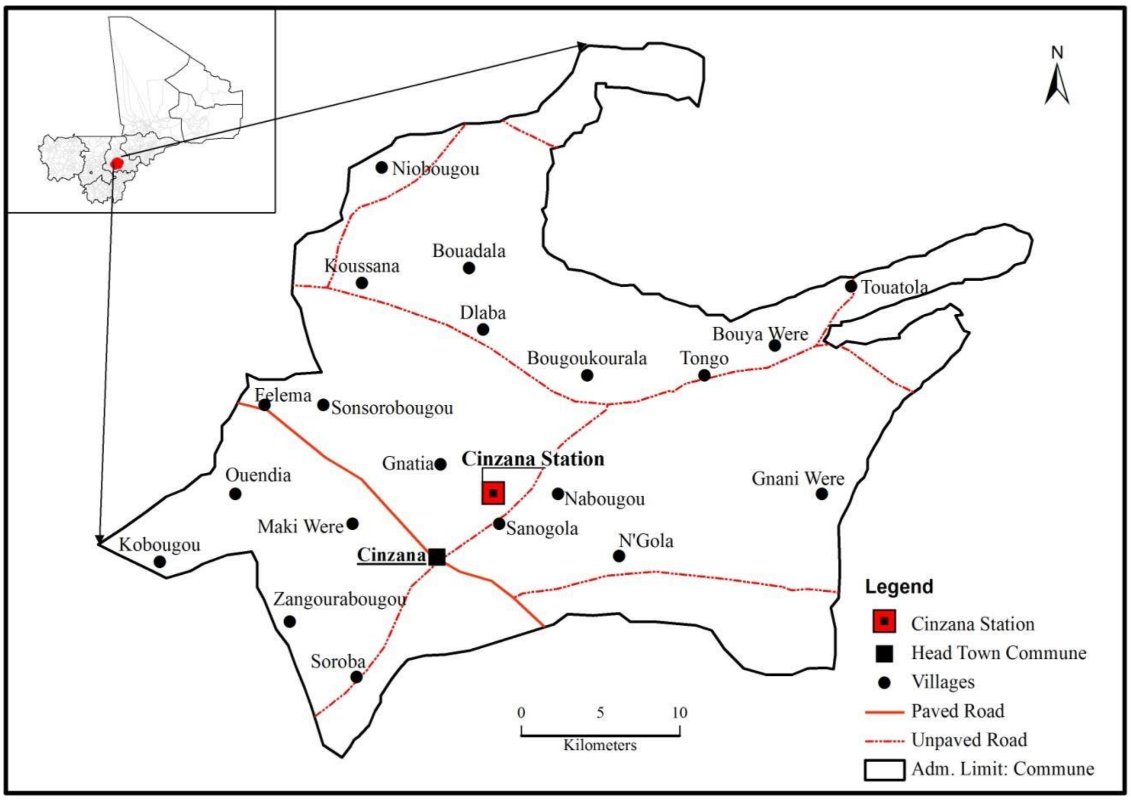
CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 The experimental site

3.1.1 Location

The study was conducted at the Agricultural Research Station of Cinzana (SRAC) in Segou Region of Mali; it is one of the Stations at the Institute of Rural Economy (IER). It is located at longitude 5°57'W, latitude 13°15'N and has an altitude of about 280 m. The SRAC covers an area of 277 ha, most of which is used for experiments. A map of the study area is indicated by Figure 3.1.



Source: Souleymane S Traore, GIS, LaboSEP, IER Sotuba, 2015

Figure 3.1: Map of experimental site in the rural community of Cinzana

3.1.2 Climate

The agricultural station is located in the sudano - sahelian zone with average temperatures under shade of 18 ºC (minimum) and 36 ºC (maximum). The daily minimum and maximum temperatures are respectively, 18 ºC and 40 ºC. The lowest temperatures are recorded from December to February and the highest from April to May.

The mean annual rainfall over 30 years is 680.4 mm. The rainy season starts in June and ends in October with mean annual rainfall between 600 to 700 mm. More than half of the rain usually falls in July and August. The rainfall is erratic and poorly distributed among the months (Figure 3.2) and years (Appendix 1). This situation is not favourable for agricultural production. The rainfall values during the growing period of 2013 and 2014 are presented in Figures 3.3 and 3.4, respectively.

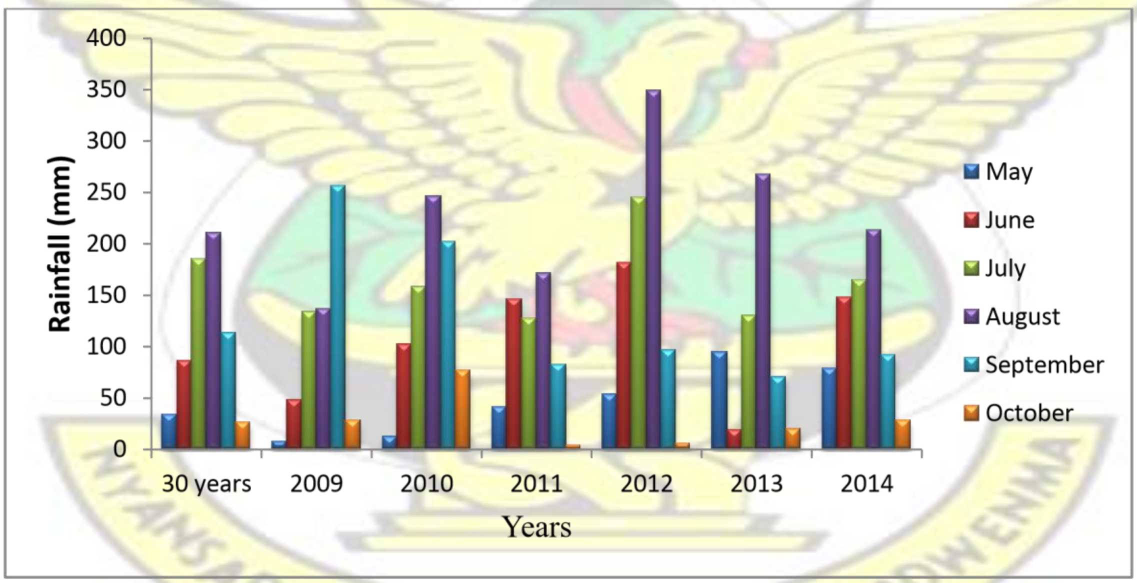


Figure 3.2: Mean monthly rainfall of 30 years compared to the last six years at Cinzana

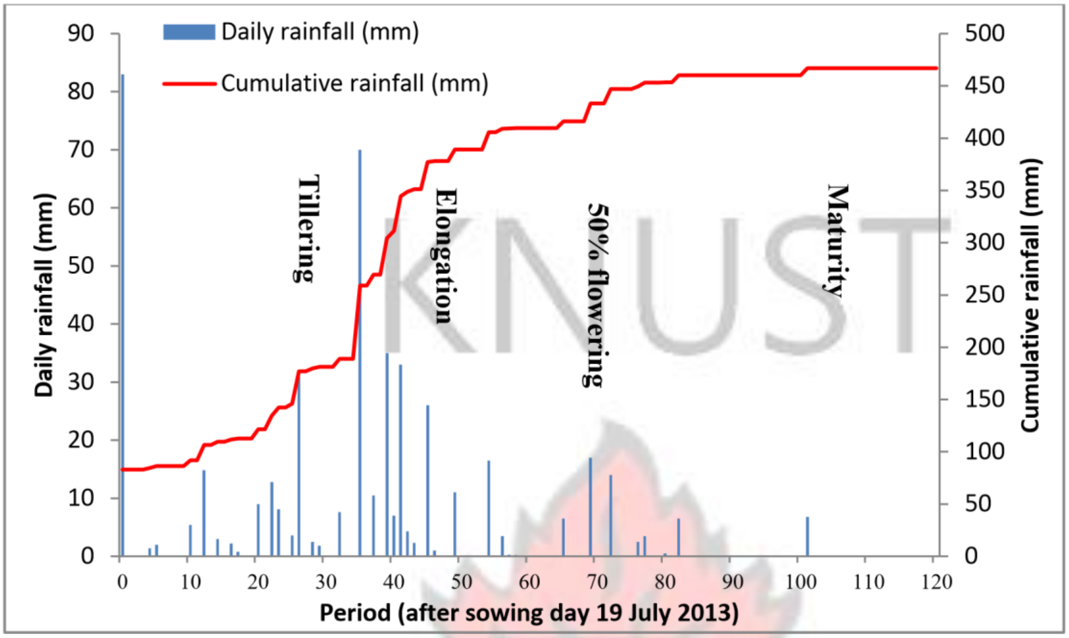


Figure 3.3: Cumulative rainfall during the crop growing period 2013 at Cinzana

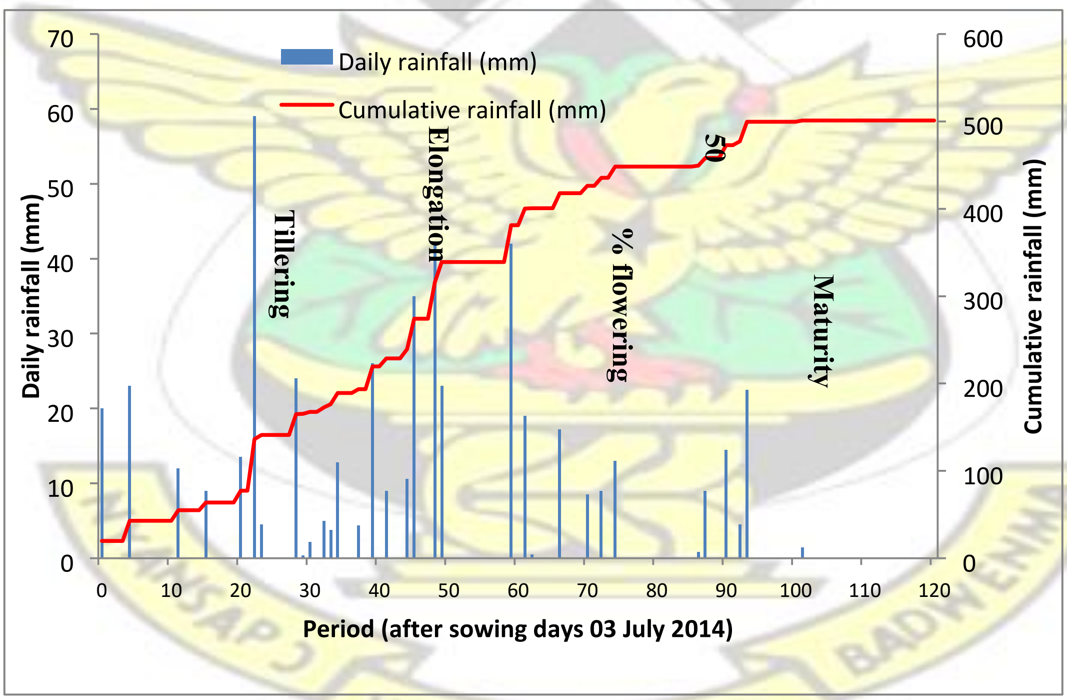


Figure 3.4: Cumulative rainfall during the crop growing period 2014 at Cinzana

3.1.3 Soil

The soil was classified as Ferric Lixisol in the FAO classification (Keita, 2002). The texture was sandy loam. The limiting factors were compact surface leading to runoff or water logging, low fertility, low CEC (3.08 $cmol_c\ kg^{-1}$) and low organic matter (0.68 %) (Keita *et al.*, 1981).

3.2 Cattle manure acquisition

Cattle manure was collected from kraal at the Agronomic Research Station of IER, Cinzana in 2013 and 2014. The manure consisting of fecal matter, urine and orts was collected from the kraal after accumulating from July to June. The kraal had no roof consequerntly, manure was exposed to the weather and lost nutrients through leaching, denetrification and volatilization.

3.3 Tilemsi rock phosphate acquisition

The rock phosphate was obtained from Toguna Agro-industrie of Mali.

3.4 Land preparation

The field was cleared manually with machete and hoe before implementing the different tillage operations. Before implementation, five soil samples were randomly taken with auger in each plot at 0 - 20 cm depth. These soil samples were thoroughly mixed, air – dried, sieved through a 2 mm mesh; composite sample was taken and stored at room temperature. Various chemical and physical properties of the samples were determined.

Apart from zai, animal traction was used for tillage operations. The ridges were made by a ridger (then tied after one day) and ripping by hoe. Zai pit was dug one week before sowing and tied ridge and conventional tillage were made one day before sowing.

3.5 Experimental design

The experiment was conducted during two rainy seasons with the same experimental layout. The experimental design was a split-plot design and arranged in randomized complete block design with three replications. The main plot factor was water harvesting techniques, while the sub plot factors were the application rates of organic manure and mineral fertilizers (Tilemsi rock phosphate and urea were used for P and N mineral sources, respectively). A sub – plot measured 6.0 x 4.5 m. The blocks were separated by 2 m alley and 1 m within the rows.

The main plot factor was water harvesting techniques:

- ✓ Conventional tillage
- ✓ Tied ridge
- ✓ Zai pit

Sub – plot factors were cattle manure and mineral fertilizer rates and their combinations presented in table 3.1

Table 3.1: Amendment applied and the amount of nutrients supplied

Treatment	Amount of nutrients (kg ha^{-1})			Nutrient source
	N	P_2O_5	K_2O	
Control (0 N: 0 P_2O_5)	0.0	0.0	0.0	
20.5 N: 23 P_2O_5	20.5	23.0	0.0	Urea and TRP
41 N: 46 P_2O_5	41.0	46.0	0.0	Urea and TRP
Cattle manure	37.3	52.0	48.5	CM
2500 kg cattle manure + 20.5 N: 23 P_2O_5	57.8	75.0	48.5	CM, Urea and TRP
2500 kg cattle manure + 41 N: 46 P_2O_5	78.3	98.0	48.5	CM, Urea and TRP

TRP: Tilemsi rock phosphate; CM: Cattle manure

3.6 Manure and mineral fertilizers application and sowing

The cattle manure was broadcasted on the same day the land was tilled (plough) on the conventional tillage and tied ridge field. The hand hoe was used to make manual line furrows at 15 cm from seed hole under conventional tillage and tied ridge. Tilemsi rock phosphate was spread in these line furrows and covered with soil using a hand hoe a day after sowing. The manure was applied in the seed hole under the zai pits the same day of its application under conventional tillage. Tilemsi rock phosphate was also applied manually by side placement under zai pits a day afer sowing.

One third (1/3) of urea was applied on the same day of Tilemsi rock phosphate application and the rest (2/3) three weeks after sowing. Urea was applied at the same period in the three tillage practices. The method of its application was the same as the Tilemsi rock phosphate. The control plots did not receive any amendment.

Improved pearl millet (*Penisetum glaucum* (L.) R.Br.), variety Indiana 05, was used as the test crop. The seeds were treated with Apron star (fungicide/insecticide) at a ratio of 10 g to 4 kg of seeds on the day of sowing. Five to ten seeds were sown per hill at a spacing of 0.8 x 0.75 m. Two weeks after emergence, the seedlings were thinned to two plants per hill giving a plant population density of 33,333 plants ha^{-1}. Weed control was carried out manually with hand hoe as and when necessary.

3.7 Growth and grain yield parameters measured

To assess the effects of water harvesting techniques and nutrient management options, data were collected on grain yield and plant growth: plant height at maturity and biomass yield at tillering, elongation, 50 % flowering and maturity stages.

3.7.1 Plant height

Plant height was measured at maturity stage. In each plot, five (5) plants were randomly selected and the height measured with a tape measure. The averages were recorded.

3.7.2 Dry matter production

Time series sampling of plant biomass was carried out for each treatment by random sampling of two hills from each sub - plot (the central portion of each plot was reserved for final harvest) at tillering, elongation, 50 % flowering, and maturity stages during both seasons. Plants were cut at ground level, kept in sampling bags and weighed.

Samples were oven dried at 70 ºC for 48 hours and weighed.

$$\text{Biomass (kg ha}^{-1}) = \frac{\text{Yield in the treatment x 10000}}{\text{Sampling area}}$$

Where:

10000: area of one hectare

Sampling area: 1.2 m^2

3.7.3 Grain yield

Plants in the area reserved for final harvest were harvested after 100 days from a delineated area of 3 m x 3 m (9 m^2) in the middle of each treatment plot leaving the border rows. Ears were sun - dried for one week. After threshing of ears of each treatment, grain was weighed at 12 % moisture content and converted into grain yield (kg ha^{-1}).

$$\text{Grain yield (kg ha}^{-1}) = \frac{\text{Yield in the treatment x 10000}}{\text{Harvest area}}$$

Where

Harvest area: 9 m^2

10000: area of one hectare

3.8 Harvest Index

The harvest index (HI) was calculated following the formula:

$$\text{HI \%} = \frac{\text{Economic yield (kg ha}^{-1})}{\text{Biological yield (kg ha}^{-1})} \times 100$$

3.9 Agronomic efficiency

Agronomic efficiency (AE) was estimated as the increase in crop yield divided by the total nutrient applied.

$$\text{AE (kg kg}^{-1}\text{)} = \frac{\text{Crop yield increase}}{\text{Nutrient applied}}$$

3.10 Soil sampling

Five soil samples were taken with auger from each plot at 0 – 20 cm after harvesting in both the first and the second years of the experiment. The five soil samples were mixed and a composite sample was taken. The soil samples were air – dried and passed through a 2 mm mesh sieve and stored at room temperature. In the zai pit technique, soil samples were taken from the pit; in the tied ridge, they were taken on the top of the ridge and in the conventional tillage, they were taken at 20 cm from the seed hole. Selected soil physical and chemical properties of the samples were determined.

3.11 Soil chemical and physical analyses

3.11.1 Chemical analysis of soil samples and plant/soil amendment samples

The following soil chemical properties were determined: pH (1:1 soil;water ratio), available P (Bray - I), total nitrogen, organic carbon, exchangeable bases (Na^{+}, Ca^{2+}, K^{+} and Mg^{2+}) and cation exchange capacity (CEC). Plant was analysed for N and P, while soil amendment samples were analyzed for total N, P, K and organic carbon and C/N ratio was calculeted.

3.11.1.1 Determination of soil pH

The soil pH was determined by the potentiometric method (1:1 soil:water ratio) proposed by McLean (1982). A 50 g of dried soil was weighed into a beaker and 50 mL of distilled water was added. The mixture was thoroughly shaken on a reciprocating shaker for 1 hour. Just before measuring pH, the beakers were shaken by hand. The pH meter was standardized with buffer solutions of pH 4.0 and 10.0. After standardization, the electrode of the pH meter was inserted in the suspension and read.

3.11.1.2 Determination of available P

The available phosphorus was extracted with Bray-I extracting solution (0.03 *M* NH_4F and 0.025 *M* HCl) as described by Olsen and Sommers (1982). Phosphorus in the extract was determined by the blue ammonium molybdate method with ascorbic acid as the reducing agent using a Technicon Auto Analyzer spectrophotometer. A 1.0 g soil sample was weighed into a 20 mL shaking bottle and 7 mL of Bray - I extracting solution added. The mixture was shaken for 1.0 minute on a reciprocating shaker and filtered through a Whatman No. 42 filter paper. An aliquot of the blank and the extract were each pipetted into a bottle and placed in auto analyzer sampler. A standard series of 0, 1.5, 3, 4.5 and 6 mg P L^{-1} were prepared from 20 mg L^{-1} KH_2PO_4. The concentration of P was measured in the standard series, samples and blanks.

Calculation

$$\text{Av. P (mg kg}^{-1}) = 7 \text{ x } (a - b)$$

Where:

a = mg kg^{-1} P measured for soil sample b

= mg kg^{-1} P measured for blank

7 = volume of Bray-I extracting solution

3.11.1.3 Determination of total nitrogen

Total nitrogen was determined by the method as described by Nelson and Sommers (1980). A 0.5 g of fine air-dried soil was weighed into a 50 mL Erlenmeyer flask. A 0.75 g of catalyst (1.55 g of Se + 1.55 g of $CuSO_4$ + 96.9 g of Na_2SO_4), and 5 mL of concentrated sulphuric acid were added. The mixture was stirred and the flask was placed on a hot plate and heated to 200 ºC, for 1 hour. Heating continued to 350 ºC, until the colour changed to light green. The flasks were removed from the plate and allowed to cool. Slowly, 25 mL of distilled water was added in small portions. When the mixture was cooled, the volume was made up to 50 mL with distilled water and mixed well. Clear aliquot of sample and blank were each pipetted and put in Technicon autoanalyzer tubes for determination of total nitrogen.

Calculation

$$\% \text{ Total N} = \frac{(a - b) \times 50}{\text{Weight of sample (g)} \times 10000}$$

Where:

a = N for soil sample b

= N for blank

10000 = coefficient of conversion from ppm N to percentage N

50 ml = final diluted volume of digest

3.11.1.4 Determination of organic carbon

Soil organic C was determined by the modified Walkley-Black wet oxidation method as outlined by Nelson and Sommers (1982). A 2 g sample of soil was weighed into 500 mL conical flask and 10 ml of 0.166 *M* (1.0 *N*) $K_2Cr_2O_7$ solution added, followed by 20 mL concentration H_2SO_4 and allowed to cool on an asbestos sheet for 30 minutes. Two hundred milliliters of distilled water was added followed by 10 ml of H_3PO_4 and then 1.0 mL of diphenylamine indicator solution. This mixture was then titrated with 1.0 *M* ferrous sulphate solution until the colour changed from a blue-black colouration to a permanent greenish colour. A blank determination was carried out in a similar way in every batch of samples analyzed without soil.

Calculation:

$$\% \text{ C} = \frac{M \text{ x (Vbl } - \text{Vs) x } 0.003 \text{ x } 1.33 \text{ x}100}{\text{g}}$$

Where:

M = Molarity of $FeSO_4$ solution

Vbl = mL of $FeSO_4$ used for blank titration

Vs = mL of $FeSO_4$ used for sample titration g

= mass of soil taken in gram

0.003 = milli - equivalent weight of C in grams (12/4000)

1.33 = correction factor used to convert the Wet combustion C value to the true C value since the Wet combustion method is about 75 % efficient in estimating C value , (i.e. 100/75 = 1.33).

3.11.1.5 Determination of exchangeable bases

The exchangeable bases were extracted using the ammonium acetate method as described by Rhoades (1982). A 2.5 g of dried soil was weighed into 100 mL centrifuge tube and 50 mL of 1.0 *M* ammonium acetate solution of pH 7.0 was added. The mixture was shaken for 30 minutes. The solution was centrifuged until the supernatant liquid was clear and the extract collected into 50 mL volumetric flask, then ammonium acetate was used to dilute the solution to 50 mL and the concentration of Ca, Mg, K and Na were read from the Agilent 4100 Microwave Plasma-Atomic Emission Spectrometer (Agilent 4100-MP-AES).

Calculation:

Using the standard series, the values of the samples and blanks were calculated as follows:

$$\text{Na}(\text{cmol}_c\ \text{kg}^{1}) = \frac{100\ \text{g x } 50\ \text{mL x } (\text{a} - \text{b})}{23\ \text{x } 1000\ \text{mL x weight of soil sample}}$$

$$\text{K}(\text{cmol}_c\ \text{kg}^{1}) = \frac{100\ \text{g x } 50\ \text{mL x } (\text{a} - \text{b})}{39.1\ \text{x } 1000\ \text{mL x weight of soil sample}}$$

$$\text{Ca}(\text{cmol}_c\ \text{kg}^{1}) = \frac{100\ \text{g x } 50\ \text{mL x } (\text{a} - \text{b})}{20\ \text{x } 1000\ \text{mL x weight of soil sample}}$$

$$\text{Mg}(\text{cmol}_c\ \text{kg}^{1}) = \frac{100\ \text{g x } 50\ \text{mL x } (\text{a} - \text{b})}{12\ \text{x } 1000\ \text{mL x weight of soil sample}}$$

Where:

23 = equivalent weight of Na

39.1 = equivalent weight of K

20 = equivalent weight of Ca

12 = equivalent weight of Mg

100 g = weight of sample for conversion to $cmol_c\ kg^{-1}$

50 mL = volume of diluted solution

1000 mL = initial volume a =

$cmol_c\ kg^{-1}$ for sample b = $cmol_c$

kg^{-1} for blank

3.11.1.6 Determination of cation exchange capacity

The cation exchange capacity (CEC) was determined using the method described by Thomas (1982). A 2.5 g of soil was weighed and mixed well with 10 g of purified sand. The mixture of soil and sand was introduced into the bottom of a perk tube cotton pad and covered by a 1 cm layer of sand. This was covered with 50 mL of 1.0 *M* ammonium acetate and percolate collected into 50 ml volumetric flasks. The volume of percolate was made up with 1.0 *M* ammonium acetate and kept for the determination of cation exchange capacity. The CEC was read from the Agilent 4100 Microwave Plasma-Atomic Emission Spectrometer (Agilent 4100-MP-AES).

Calculation

$$CEC\ (cmol_c\ kg^{-1}) = (a - b) \times h\ (cm)$$

Where:

a = value in $cmol_c\ kg^{-1}$ for the sample b =

value in $cmol_c\ kg^{-1}$ for blank h = height of

the peak observed from graph

3.11.1.7 Determination of total nitrogen and phosphorus (plant and soil amendment)

Wet digestion of plant and soil amendment

Plant samples were wet digested following the procedure described by Nelson and Sommers (1980). The soil amendment (manure) followed the same process as plant. A 0.5 g of the dried plant material was taken into 50 mL volumetric flask and 2.5 mL of concentrated sulphuric acid and one ml of hydrogen peroxide were added. The suspension was swirled and placed on hot plate and heated at 270 °C for 10 minutes. The flasks were removed from the plate and allowed to cool for 10 minutes after which 1.0 ml H_2O_2 was added and heated for 10 minutes at the same temperature. Heating, cooling and adding of 0.5 mL of H_2O_2 sequences were repeated until the digest was colourless. The digest was removed from the hot plate and the volume was made up with distilled water to 50 mL and used to determine N and P. The same procedure was used with manure

Determination of total nitrogen

Total nitrogen was measured using the Technicon Auto Analyzer.

Calculation:

$$\%\ \text{Total N} = \frac{(a - b) \times 50}{\text{Weight of plant sample (g)} \times 10000}$$

Where:

a = N for plant sample b

= N for blank

10000 = coefficient of conversion from ppm N to percentage N

50 mL = final diluted volume of digest

Determination of total phosphorus

Total phosphorus was determined using the Technicon Auto Analyzer, manifold P Bray -I.

Calculation:

$$\% \text{ P} = \frac{[(\text{a} - \text{b}) \text{ x } 50]}{\text{weight of plant sample (g) x } 10000}$$

Where:

a = P for plant sample b

= P for blank

50 mL = final diluted volume of digest and

10000 = coefficient of conversion from ppm P to percentage P

3.11.1.8 Nutrient uptake

Nutrient uptake was calculated as the product of nutrient concentration in grain or straw and the yield.

N uptake = Dry weight x concentration of N content in plant (grain and straw samples)

P uptake = Dry weight x concentration of P content in plant (grain and straw samples)

3.11.1.9 Nitrogen and phosphorus utilization efficiencies

The Nutrient Utilization Efficiency (NUE) was calculated following the formula by (Christianson and Vlek, 1991). It is the ratio of grain or biomass yield to the total nutrient absorbed.

$$\text{NUE (kg kg}^{-1}) = \frac{\text{Yield}}{\text{Total nutrient absorbed}}$$

Where:

Yield, millet straw and grain yield in kg ha^{-1};

Total nutrient absorbed: Total nutrient uptake in pearl millet straw and grain (kg ha^{-1}).

3.11.2 Soil physical analysis

The following soil physical properties were determined: particle size, soil gravimetric moisture content, bulk density, volumetric moisture content and rainwater use efficiency.

3.11.2.1 Determination of soil textural class

The hydrometer method was used to determine the soil particle size (Anderson and Ingram, 1993). The weight of 51 g of air – dry soil (< 2 mm) was transferred into a 250 mL beaker. A 50 mL calgon solution was dispensed into the soil together with 100 mL of deionized water. The suspension was vigorously stirred for 1 min using a glass rod and allowed to stand undisturbed for 30 minutes before transferring to the mixer for mixing using medium speed for 15 minutes. After mixing, the suspension was transferred to the sedimentation cylinder and plunged. The mixture was made up to 1000 mL with deionized water and plunged vigorously. This was immediately continued by placing the soil hydrometer and sliding it slowly into the suspension until it floated, noting the time. The first hydrometer (H_1) and temperature (T1) readings at 40 seconds were recorded. Duplicate readings were taken. After the first two readings of hydrometer (H_1) and temperature, the suspension was allowed to stand undisturbed for 3 hours before the second hydrometer readings (H_2) and the temperature of the suspension (T2) were taken.

Calculation:

$$\% \text{ Sand} = [100 – (H_1 + 0.2) \text{ x } (T_1 – 20) – 2] \text{ x } 2$$

$$\% \text{ Clay} = [(H_2 + 0.2) \text{ x } (T_2) – 2] \text{ x } 2$$

$$\% \text{ Silt} = 100 – (\% \text{ sand} + \% \text{ clay})$$

Where

H_1 = average of first two hydrometer readings T_1

= average of first two temperature reading

H_2 = second hydrometer reading
T_2 = second temperature reading

3.11.2.2 Soil gravimetric moisture content

Three soil samples were taken at 0 – 20 and 20 - 40 cm depth in each sub-plot with auger every 15 days from sowing to crop maturity (crop cycle 100 days). Gravimetric moisture content was determined using the method described by Marshall and Holmes (1988). Soil samples were taken from the zai pit, tied ridge and conventional tillage plots as described at section 3.10. A 10 g soil was placed in a preweighed container (W1) and the joint weight of the soil and container (W2) recorded. The soil together with the container was oven dried at 105^{o}C for 24 h. The oven dried weight was recorded (W3) and the difference in oven dried and fresh soil was calculated.

Calculation:

$$\theta m\ (\%) = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

Where:

W_1 is the weight of empty can + lid

W_2 is weight of can + lid + fresh soil

W_3 is weight of can + lid + oven – dried soil

3.11.2.3 Bulk density determination

The bulk density was determined at the 0 - 10, 10 -20, 20 – 30 and 30 - 40 cm depths using the core sampler method at 45 and 90 days after sowing. Forty-five (45) days corresponded with crop elongation accompanied by greaterwater and nutrient demand, and 90 was the maturity stage of crop. Two samples were taken per depth in each subplot. Soil samples were taken from the zai pit, tied ridge and conventional tillage plots as described at section 3.10. A 400 cm^3 cylinder was used in taking the core samples. These were oven - dried at 105 ºC to constant weight for 48 hours and weighed. The bulk density (ρb) was calculated as:

$$\text{Bulk density } (\rho b)\ (g\ cm^{-3}) = \frac{Ms}{Vt}$$

Where:

Ms = Oven dry weight of soil (g)

Vt = total volume of cylinder ($\pi r^2 h$) cm^3)

3.11.2.4 Volumetric moisture content

The volumetric moisture content (Θv) was calculated as:

$$v\ (cm^3 cm^{-3}) = \frac{\theta m}{\rho w} \times \rho b$$

Where:

ρb = soil bulk density ρw

= density of water

3.11.2.5 Depth of water

Depth of water was calculated from volumetric moisture content and depth of soil as follows:

$$z\ (mm) = v \times \text{depth of soil}$$

3.11.2.6 Rainwater use efficiency

Rainwater use efficiency: the efficiency with which rainfall is converted to grain over multiple crops.

Water use efficiency was calculated after crop grain harvesting according to the formula used by GRDC (2009).

$$RWUE(\text{kg Grain mm}^{-1}\ \text{rainfall}) = \frac{\text{Total grain yield (kg ha}^{-1})}{\text{Total rainfall (mm)}}$$

3.12 Combined effects of water harvesting techniques, soil amendments application on yield of pearl millet

The added benefit from the combined application of manure and mineral fertilizer was calculated using the following formula (Vanlauwe *et al.*, 2002):

$$AB = Y_{comb} – (Y_{fert} – Y_{con}) – (Y_{cat} – Y_{con}) – Y_{con}$$ Where:

AB = represents the added benefits,

Y_{con} = the mean grain yield from control treatment,

Y_{fert} = the mean grain yields from the sole application of mineral fertilizer,

Y_{cat} = the mean grain yields from the sole application of manure, and Y_{comb} = the mean grain yields from the combined application of mineral fertilizer and manure.

3.13 Evaluation of N and P partial balance under water harvesting and soil amendments application for pearl millet

Before crop sowing and after harvesting, soil sampling was done at 0 - 20 cm depth for each plot to determine the soil nutrient partial balance. It was determined by the difference between added and exported nutrients (Kihara *et al.*, 2011).

Partial nutrient balance = Input – Output

Where:

Input: mineral fertilizer and manure

Output: grain and straw uptake

The estimates excluded inputs in wet and dry decomposition, sedimentation, and nutrient accessions by deep roots from subsoil layers, and outputs by leaching, erosion, runoff, and gaseous losses.

3.14 Economic analysis

The economic viability of manure incorporation was assessed on partial factor of productivity, the basis of net farm benefit (NFB) and value cost ratio (VCR). The partial budgeting technique for on-farm research (CIMMYT, 1988) was used to evaluate the NFB. Crop prices and the operational cost were the average prices prevailing in the study area during the trial. Gross benefit accruing from each treatment was calculated as the product of the grain yield from the treatment and the average unit price of the grains. The variable input costs were the actual prices of manure and mineral fertilizer, land preparation, sowing, incorporation of soil amendments, weeding, threshing and transportation of millet ears and manure. The NFB was defined as the difference between gross benefit and variable input cost.

The VCR was calculated as follows:

$$VCR = \frac{(Y_{MxF} - Y_C) \text{ x } P_G}{(Q_M x P_M) + (Q_F x P_F)}$$

Where:

Y_{MxF} is the grain yield from plots with manure and mineral fertilizer application,

Y_C is the grain yield from control plots,

P_G is the unit price of grain yield,

P_M is unit price for manures incorporated,

Q_M is the quantity of manures applied,

P_F is the unit price of mineral fertilizer applied and

Q_F is the quantity of mineral fertilizer applied.

$$(\text{kg grains kg}^{-1}) = \frac{\text{rain yield } (\text{kg ha}^{-1})}{\text{rate of nutrient applied (}}$$

Where:

PFP: partial factor productivity

3.15 Statistical analysis

The field data were analyzed with GenStat package 9^{th} edition. Soil physical and chemical properties, growth parameters, nutrient use efficiency, straw and grain yields were analyzed using analysis of variance (ANOVA) and the means were separated using least significant difference (Lsd) method at 5 % of probability. Repeated measurements were used to analyze soil gravimetric moisture content. Graphical presentations were done using Excel software.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Initial chemical characteristics of cattle manure and Tilemsi rock phosphate

4.1.1 Results

The chemical characteristics of manure and Tilemsi rock phosphate used during the two years are presented in Table 4.1. Manure used in the two years had similar total nitrogen, total phosphorus and total potassium contents. The C/N ratio of the manure ranged from 20.78 to 22.60. The Tilemsi rock phosphate on the other hand contained 28.05 % P_2O_5.

Table 4.1: Chemical analysis of cattle manure and Tilemsi rock phosphate

Soil	Total	Total	Total	Total	Organic

amendments	N	P	P_2O_5	K_2O	C	C/N
	----------------------------------%--					
Cattle manure 2013	1.49 ± 0.19	0.91	2.08 ± 0.26	1.94 ± 0.09	33.67 ± 1.06	22.60
Cattle manure 2014	1.47 ± 0.06	0.86	1.97 ± 0.15	1.88 ± 0.04	30.55 ± 0.79	20.78
Tilemsi rock phosphate	-	-	28.05 ± 0.46	-	-	-

*Values are means of triplicate samples; ± standard deviation

4.1.2 Discussion

Using the guidelines of Odedina *et al.* (2014), the levels of nitrogen, phosphorus and potassium in the manure were considered to be high (Table 4.1). It was therefore a rich source of plant nutrients. The C/N ratio of the manure was lower than the critical C/N of 25 required for organic materials to mineralize (Myers *et al.*, 1994). The manure used in the study could potentially release nitrogen for enhanced crop growth. The result of the present study indicated that rock phosphate contained 28.05 % P_2O_5 and which is in close agreement with 28.80 % P_2O_5 in Tilemsi rock phosphate reported by Zapata and Roy (2004). Considering its reactivity to be medium (Zapata and Roy, 2004), the Tilemsi rock phosphate was potentially a good source of P for plants.

4.2 Initial soil physical and chemical characteristics of the experimental site

4.2.1 Results

The initial soil chemical and physical properties to the depth of 0 – 20 cm are presented in Table 4.2. The results showed that soil pH was moderately acid (5.83) with low total nitrogen (0.02%), available phosphorus (4.08 mg kg^{-1}) and very low organic carbon (0.39%). The exchangeable bases of the soil were adequate, in the order of 1.35, 0.78 and 0.20 $cmol_c$ kg^{-1} for Ca, Mg and K, respectively, while Na was low. The cation exchange capacity was 2.47 $cmol_c$ kg^{-1}.

The texture was sandy loam with 72.54 % sand, 23.24 % silt and 4.22 % clay. The bulk density was 1.53 g cm^{-3}.

Table 4.2: Initial soil physical and chemical characteristics of the experimental site

Soil parameters	0 – 20 cm depth
pH (1:1 H_2O)	5.83 ± 0.11
Organic C (%)	0.39 ± 0.02
Total N (%)	0.02 ± 0.003
Available P (mg kg^{-1})	4.08 ± 0.66
Exchangeable bases ($cmol_c$ kg^{-1})	
K	0.20 ± 0.05
Ca	1.35 ± 0.14

Mg	0.78 ± 0.14
Na	0.14 ± 0.03
CEC (cmol$_c$ kg^{-1})	2.47 ± 0.51
Physical parameters	
Bulk density (g cm^{-3})	1.53 ± 0.06
Sand %	72.54 ± 0.63
Silt %	23.24 ± 0.53
Clay %	4.22 ± 0.31
Texture	Sandy loam

*Values are means of triplicate samples from each plot; ± standard deviation

4.2.2 Discussion

In relation to the threshold values for soil nutrient contents reported by Fairhurst (2012), organic carbon, total nitrogen, available phosphorus and exchangrable sodium were low, while exchangeable potassium, calcium and magnesium were adequate in the soil. The initial pH value (5.83) of the experimental site was different from the findings of Kouyate *et al.* (2012) who found a pH of 6.00 at Cinzana in Mali. The low pH could be attributed to soil aluminium toxicity. According to Whalen *et al.* (2000), in sandy soil, most agricultural crops perform well in the range of pH 5.6 to 7.5. Soil organic carbon (0.39 %) of the experimental site was different from the findings of Doumbia *et al.* (1993) who found 0.13 % organic carbon content in the initial soil at Cinzana Mali.

The initial total nitrogen content (0.02 %) was very low and could be a constraint for the crop growth and yields. The initial available phosphorus content (4.08 mg kg^{-1}) in the experimental site was low in relation to the threshold value of 15 mg kg^{-1} reported by Fairhurst (2012). The available P value obtained in the current study indicates the need to supply phosphorus through inorganic fertilizer or organic resources to ensure good crop production. The initial soil CEC of the experimental site (2.47 $cmol_c$ kg^{-1}) was lower than 13.80 $cmol_c$ kg^{-1} reported by Kouyate *et al.* (2012) in the same study area. The CEC value recorded was lower than the optimum range of 5 to 20 $cmol_c$ kg^{-1} as reported by Yeboah *et al.* (2013). The soil was classified as Ferric Lixisol in FAO classification (Keita, 2002).

4.3 Millet growth and yield as affected by water harvesting techniques and soil amendments application

4.3.1 Results

4.3.1.1 Millet height as affected by water harvesting techniques and soil amendments application

Millet height during 2013 and 2014 cropping seasons are presented in Table 4.3. During the 2013 cropping season, millet height was significantly affected by water harvesting techniques as well as by soil amendments management. The following trend was observed under water harvesting techniques: zai > tied ridge > convention tillage. The trend under organic amendment management options was M 2500 kg ha^{-1} > M 0 kg ha^{-1} and under the mineral fertilizers it was 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} > 0 kg N: 0 kg P_2O_5 ha^{-1}. During the 2014 cropping season, water harvesting techniques and soil amendments significantly ($P < 0.05$) affected pearl millet height. The effect of water harvesting and soil amendments on pearl millet height followed the same trend as in 2013. The combined use of water harvesting techniques and manure application significantly ($P < 0.05$) increased plant height at maturity stage in 2013 (Appendix 2). The combined use of zai with manure at 2500 kg ha^{-1} recorded the highest plant height.

Table 4.3: Effects of water harvesting techniques and soil amendments on pearl millet height in 2013 and 2014 cropping seasons

Treatments	Plant height (cm)	
	2013	2014
	Maturity	Maturity stage Stage
Water harvesting techniques (A)		
Conventional tillage	266.60	301.70
Tied ridge	297.20	330.10
Zai	303.80	330.90
Fpr	0.03	0.04
Lsd (0.05)	26.10	23.05

Organic manure (B) (kg ha^{-1})		
M0	281.10	308.50
M 2500	297.30	333.20
Fpr	< 0.001	< 0.001
Lsd (0.05)	6.60	8.86
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	280.00	302.50
20.5 N: 23 P_2O_5	295.50	328.90
41 N: 46 P_2O_5	291.90	331.20
Fpr	0.001	< 0.001
Lsd (0.05)	8.08	10.85
Int A x B	0.005	ns
Int A x C	ns	ns
Int B x C	ns	ns
Int A x B x C	ns	ns
CV (%)	4.10	5.00

Int: Interaction, ns: not significant at F probability 5 %

4.3.1.2 Effects of water harvesting techniques and soil amendments on total dry matter production

Pearl millet total dry matter production (TDM) is presented in Table 4.4. In 2013 water harvesting techniques significantly ($P \leq 0.05$) increased TDM production at elongation, 50 % flowering and maturity stages. Zai recorded the highest value (143.20 g plant^{-1}) at maturity, while the lowest value of total dry matter was obtained by conventional tillage (112.40 g plant^{-1}). Manure produced better biomass yield than the control at different crop growth stages. Manure treatment gave the highest TDM (144.90 g plant^{-1}), while the control treatment gave the lowest (109.30 g plant^{-1}) at maturity. Total dry matter increased at the different growth stages with mineral fertilizer. The maximum TDM yield was obtained by the treatment 41 kg N: 46 kg P_2O_5 ha^{-1} (139.0 g $plant^{-1}$) and the minimum by the control (109.30 g $plant^{-1}$) at maturity.

In 2014 water harvesting techniques did not significantly ($P > 0.05$) affect total dry matter production at all growth stages. Manure treatment increased biomass yield at tillering, elongation and maturity stages. The highest biomass yield (252.70 g $plant^{-1}$) was reported by manure treatment, while the control treatment gave the lowest (193.40 g $plant^{-1}$) at maturity. Mineral fertilizer application enhanced TDM production at elongation, 50 % flowering and maturity stages. The highest TDM was recorded by the treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} (239.40 g $plant^{-1}$) and minimum by the control (198.50 g $plant^{-1}$).

Interactive effect of water harvesting techniques and organic manure significantly ($P < 0.03$) affected biomass production at tillering and elongation stages, respectively in 2013 and 2014 cropping seasons (Appendix 3). The combined use of tied ridge with manure at 2500 kg ha^{-1} had the highest TDM at elongation stage. Combined use of water harvesting techniques and mineral fertilizer affected biomass production at tillering, elongation and 50 % flowering stages in 2013 and 2014 copping seasons (Appendix 4).

The combined use of either zai or conventional tillage with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} yielded the highest TDM at 50 % flowering stage. Organic manure combined with mineral fertilizer influenced TDM at elongation and 50 % flowering stages in 2014 cropping season (Appendix 5). Application of manure at 2500 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} produced the highest TDM at 50 % flowering stage.

Table 4.4: Effects of water harvesting techniques and soil amendments on dry matter production in 2013 and 2014 cropping seasons

Treatments	Dry matter production (g $plant^{-1}$)							
	2013				2014			
	Tillering stage	Elongation stage	50 % flowering stage	Maturity stage	Tillering stage	Elongation stage	50 % flowering stage	Maturity stage
Water harvesting techniques (A)				112.40				
C. tillage	1.26	23.60	94.60		2.10	51.70	201.80	210.00
Tied ridge	1.38	28.80	116.90	125.80	1.86	46.30	200.00	237.70
Zai	1.47	37.10	130.20		1.77	39.30	142.90	221.40
				143.20				
Fpr	0.19	0.045	0.03	0.05	0.59	0.23	0.15	0.29
Lsd (0.05)	ns	9.81	23.16	22.91	ns	ns	ns	ns
Organic manure (B) (kg ha^{-1})								
M0	1.24	24.60	99.70	109.30	1.60	39.70	174.00	193.40
M 2500	1.51	34.70	128.10	144.90	2.22	51.90	189.10	252.70
Fpr	0.002	< 0.001	< 0.001	< 0.001	0.005	< 0.001	0.16	< 0.001
Lsd (0.05)	0.17	4.76	12.47	10.68	0.410	6.77	ns	24.76
Mineral fertilizer (C) (kg ha^{-1})								
0 N: 0 P_2O_5	1.37	24.70	104.30	109.30	1.64	39.60	157.70	198.50
20.5 N: 23 P_2O_5	1.35	31.20	111.50	132.70	2.15	49.10	181.80	239.40
41 N: 46 P_2O_5	1.40	33.60	125.90	139.30	1.94	48.60	205.10	231.20
Fpr	0.85	0.01	0.02	< 0.001	0.13	0.04	0.004	0.02
Lsd (0.05)	ns	5.83	15.28	13.08	ns	8.29	26.50	30.32
Int A x B	< 0.001	ns	ns	ns	ns	0.03	ns	ns
Int A x C	ns	0.03	0.03	ns	0.04	0.001	0.02	ns
Int (B x C)	ns	ns	ns	ns	ns	0.001	0.03	ns

Int A x B x C	ns	ns	ns	ns	ns	ns	ns	ns
CV (%)	22.10	28.70	19.70	15.10	39.10	26.60	21.40	20.00

Int: Interaction, C. tillage: Conventional tillage, ns: not significant at F probability 5 %

4.3.1.3 Effects of water harvesting techniques and soil amendments and their interaction on straw and grain yields

The results of straw and grain yields as affected by water harvesting techniques and soil amendments application showed that the yields were higher in 2014 than 2013 cropping seasons (Table 4.5).

In 2013 pearl millet grain yield significantly ($P = 0.004$) increased under zai by 47 % followed by tied ridge (31.37 %) compared to conventional tillage. On the other hand, manure increased the grain yield by 45 % over the control, while the application of mineral fertilizers (Tilemsi rock phosphate and urea) increased grain yield on the average by 54 % compared with the control regardless of water harvesting techniques. Combined application of manure and mineral fertilizer significantly ($P < 0.001$) increased the millet grain yield (Table 4.6). Application of manure at 2500 kg ha^{-1} and mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} recorded the highest grain yield (1728 kg ha^{-1}), while the lowest grain yield was obtained under no application of manure and mineral fertilizer (846 kg ha^{-1}). However, the interactive effect of water harvesting techniques and soil amendments (manure and mineral fertilizer) was not significant ($P > 0.05$) (Table 4.5).

In 2014 higher grain yields were recorded compared to the 2013 cropping season. The grain yield increased on the average by 67 and 53 %, respectively in the zai and the tied ridge plots irrespective of soil amendments applied. The application of manure significantly increased ($P < 0.001$) the grain yield by 29 % over the control, whereas grain yield increase of 34 % was recorded with the mineral fertilizer. There was a significant interaction ($P = 0.045$) between manure and mineral fertilizer applications on grain yield.

Yet no significant interaction was recorded between water harvesting techniques and soil amendments applied in the current study (Table 4.5).

The straw yield recorded in this study followed the same trend as the grain yield in 2013 and 2014 cropping seasons. However, in 2014 a significant interaction (P = 0.048) was observed between water harvesting techniques and manure application on millet straw yield while all the other interactions remained non significant (Table 4.7). The combined use of zai with manure at 2500 kg ha^{-1} led to the highest amount of straw yield (6577 kg ha^{-1}). The use of convectional tillage without manure gave the lowest straw yield (3861 kg ha^{-1}).

Table 4.5: Effects of water harvesting techniques and soil amendments on pearl millet straw and grain yields in 2013 and 2014 cropping seasons

Treatments	Straw yield	Grain yield	Straw yield	Grain yield
	2013		2014	
	---------------------------- ($kg\ ha^{-1}$)		---------------------------	
Water harvesting techniques (A)				
Conventional tillage	3148	781	4162	1035
Tied ridge	3946	1026	5696	1587
Zai	4440	1151	5426	1730
Fpr	0.048	0.004	0.025	< 0.001
Lsd (0.05)	957.60	136.60	986.90	136.10
Organic manure (B) ($kg\ ha^{-1}$)				
M0	3397	806	4327	1245
M2500	4291	1166	5862	1603
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	454.50	99.40	553.80	151.00
Mineral fertilizers (C) ($kg\ ha^{-1}$)				
0 N: 0 P_2O_5	3371	725	4331	1186
20.5 N: 23 P_2O_5	4005	1078	5445	1564
41 N: 46 P_2O_5	4157	1155	5508	1603
Fpr	0.02	< 0.001	0.002	< 0.001
Lsd (0.05)	556.70	121.80	678.20	185.00
Int A x B	ns	ns	0.048	ns
Int A x C	ns	ns	ns	ns
Int B x C	ns	< 0.001	ns	0.045
Int A x B x C	ns	ns	ns	ns
CV (%)	21.30	18.10	19.60	18.70

Int: Interaction, ns: not significant at F probability 5 %

Table 4.6: Interactive effect of manure and mineral fertilizer on pearl millet grain yield in 2013 and 2014 cropping seasons

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Grain yield (kg ha^{-1}) 2013	2014
M0	0 N: 0 P	433	846
	20.5 N: 23 P_2O_5	1044	1399
	41 N: 46 P_2O_5	1111	1428
M 2500	0 N: 0 P_2O_5	1017	1525
	20.5 N: 23 P_2O_5	940	1728
	41 N: 46 P_2O_5	1370	1716
	Fpr	< 0.001	0.045
	Lsd (0.05)	172.20	261.60

Table 4.7: Interactive effect of water harvesting techniques and manure on pearl millet straw yield in 2014 cropping season

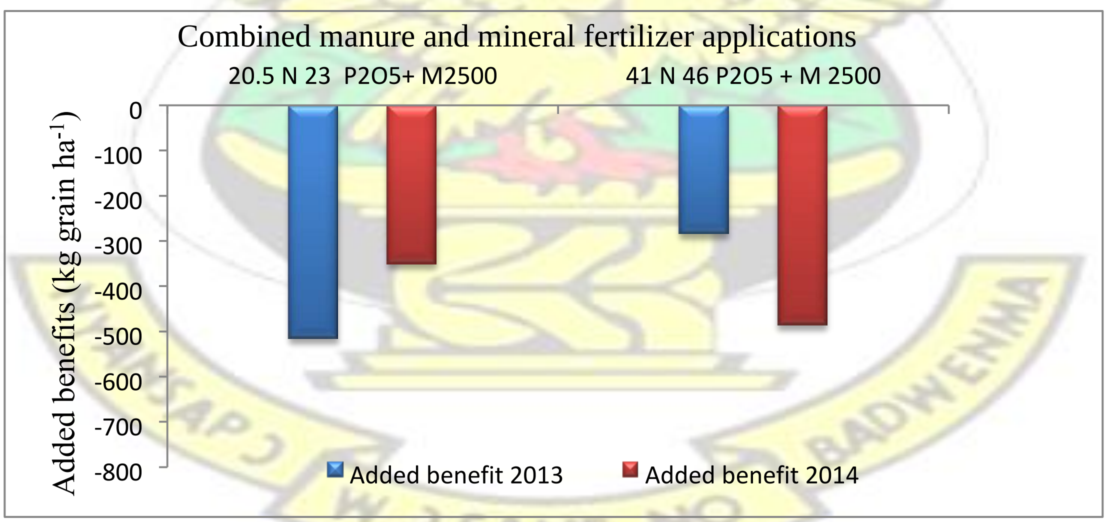
Water harvesting techniques	Manure (kg ha^{-1})	Straw yield (kg ha^{-1})
C. tillage	M0	3861
	M 2500	4463
Tied ridge	M0	4847
	M 2500	6546
Zai	M0	4275
	M 2500	6577
	Fpr	0.048
	Lsd (0.05)	959.20

C. tillage: Conventional tillage

4.3.1.4 Added benefits from combined use of water harvesting techniques and soil amendments on grain yield of pearl millet

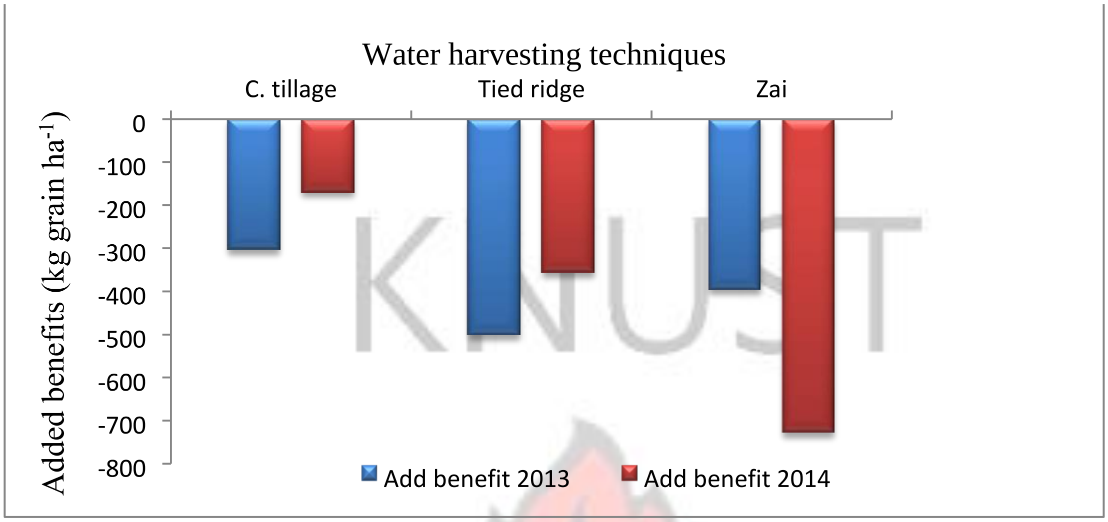
The change in grain yield resulting from the interaction of manure and N and P fertilizer is shown in the Figure 4.1. In both cropping seasons, the added benefit of combined manure and mineral fertilizer was not significant. The added benefit of grain yield ranged from -517 to -285 kg grain ha^{-1} in the first year for treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} and 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1}, respectively. In the second year, the observed values were -351 and -487 under treatments 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} and 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1}, respectively.

The added benefit was negative under water harvesting techniques as shown in Figure 4.2. Zai recorded -396 and -729 kg grain ha^{-1} followed by tied ridge (-502 and -357 kg grain ha^{-1}) and conventional tillage (-304 and -171 kg grain ha^{-1}), respectively in 2013 and 2014.



Added benefits with no error bars were not significantly different ($p > 0.05$)

Figure 4.1: Effects of manure and mineral fertilizer on added benefits



C. tillage: Conventional tillage

Added benefits with no error bars were not significantly different (p > 0.05) Figure 4.2: Effects of water harvesting techniques on added benefits

4.3.1.5 Harvest Index

In the two cropping seasons, water harvesting techniques did not significantly ($P > 0.05$) affect harvest index (Table 4.8). However, soil amendment treatments significantly ($P < 0.001$) influenced harvest index.

In 2013 harvest index (HI) values in response to water harvesting techniques ranged from 24.86 to 26.58 % in the order of conventional tillage = tied ridge = zai. Soil amendment treatments were significantly different ($P < 0.05$). The organic manure had a higher HI (27.77 %) than the control (23.85 %) and the HI values for the mineral fertilizer treatments ranged from 28.10 to 22.01 % in the decreasing order of 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} > 0 kg N: 0 kg P_2O_5 ha^{-1}.

In 2014 there were no significant differences among water harvesting techniques and soil amendment treatments. The harvest index values from water harvesting techniques ranged from 25.20 to 32.60 %. Soil amendment treatments were not significantly different ($P > 0.05$). However, the control had a higher value (29.50 %) than the manure treatment value (28.50 %) and the values for mineral fertilizer ranged from 27.60 to 30.40 % in the order of 0 kg N: 0 kg P_2O_5 ha^{-1} = 20.5 kg N: 23 kg P_2O_5 ha^{-1} = 41 kg N: 46 kg P_2O_5 ha^{-1}.

Table 4.8: Effects of water harvesting techniques and soil amendments on pearl millet harvest index in 2013 and 2014 cropping seasons

	Harvest index (%)	
Treatments	2013	2014
Water harvesting techniques (A)		
Conventional tillage	24.86	25.20
Tied ridge	26.58	29.30
Zai	26.00	32.60
Fpr	0.64	0.19
Lsd (0.05)	ns	ns
Organic manure (B) (kg ha^{-1})		
M0	23.85	29.50
M 2500	27.77	28.5
Fpr	0.014	0.65
Lsd (0.05)	3.07	ns
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	22.01	27.60
20.5 N: 23 P_2O_5	27.32	29.10
41 N: 46 P_2O_5	28.10	30.40
Fpr	0.005	0.57
Lsd (0.05)	3.77	ns
Int A x B	ns	ns
Int A x C	ns	ns
Int B x C	ns	ns
Int A x B x C	ns	ns
CV (%)	21.4	26.8

Int: interaction, ns: not significant at F probability 5 %

4.3.1.6 Agronomic efficiency

The effects of N and P fertilizers on agronomic efficiency (AE) are summarized in Table 4.9. In the two cropping seasons, agronomic efficiency was not significantly ($P > 0.05$) different under water harvesting techniques. However, there was a significant effect of soil amendments ($P < 0.001$) on agronomic efficiency. The interactive effects of water harvesting techniques and the soil amendments were not significantly different.

In 2013 the N agronomic efficiency values under water harvesting techniques ranged from 13.94 to 19.32 kg kg^{-1} and the P agronomic efficiency ranged from 11.63 to 16.12 kg kg^{-1} in the order of zai = tied ridge = conventional tillage. The soil amendment treatments significantly ($P < 0.001$) affected N and P agronomic efficiencies. The AE for nitrogen was in the order of 20.5 kg N: 23 kg P_2O_5 ha^{-1} > M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} and the trend for P AE was 20.5 kg N: 23 kg P_2O_5 ha^{-1} > M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1}. The highest AE value was recorded by the 20.5 kg N: 23 kg P_2O_5 ha^{-1} treatment with 29.82 kg kg^{-1} N and 26.58 kg kg^{-1} P, whilst the lowest values were reported under 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} treatment with 11.19 kg kg^{-1} N and 9.13 kg kg^{-1} P, respectively.

In 2014 the agronomic N efficiency values under water harvesting techniques ranged from 12.23 to 23.10 kg kg^{-1} and the P values varied from 10.30 to 19.19 kg kg^{-1} in the order of conventional tillage = tied ridge = zai. The soil amendment treatments significantly ($P < 0.001$) affected the agronomic N and P efficiencies. The agronomic N efficiency followed the order of 20.5 kg N: 23 kg P_2O_5 ha^{-1} > M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} and the agronomic P efficiency trend was 20.5 kg N: 23 kg P_2O_5 ha^{-1} > M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1}. The highest AE for N and P value was recorded by 20.5 kg N: 23 kg P_2O_5 ha^{-1}. The interactive effects of water harvesting techniques, manure and mineral fertilizer did not significantly ($P > 0.05$) influence agronomic efficiency.

Table 4.9: Effects of water harvesting techniques and soil amendments on N and P agronomic efficiency in 2013 and 2014 cropping seasons

Treatments	Agronomic efficiency (kg kg^{-1})			
	2013		2014	
	NAE	PAE	NAE	PAE
Water harvesting techniques (A)				
Conventional tillage	13.94	11.63	12.23	10.30
Tied ridge	15.69	13.09	17.31	14.42
Zai	19.32	16.12	23.10	19.19
Fpr	0.23	0.25	0.12	0.12
Lsd (0.05)	ns	ns	ns	ns
Soil amendments (SA) (kg ha^{-1})				
0 N: 0 P_2O_5	-	-	-	-
M 2500 kg	15.66	11.85	18.47	13.78
20.5 N: 23 P_2O_5	29.82	26.58	26.99	24.06
41 N: 46 P_2O_5	12.37	11.03	15.70	13.99
20.5 N: 23 P_2O_5 + M 2500	11.75	9.04	15.40	12.20
41 N: 46 P_2O_5 + M 2500	11.97	9.56	11.19	9.13
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	5.80	5.05	5.87	4.86
Int A x SA	ns	ns	ns	ns
CV (%)	36.50	38.10	34.40	34.10

Int: interaction, ns: not significant at F probability 5 %

4.3.2 Discussion

4.3.2.1 Millet height as affected by water harvesting techniques and soil amendments application

Millet grown under water harvesting techniques (zai and tied ridge) gave the highest height values compared to the conventional tillage. The highest plant height values obtained with water harvesting techniques could be attributed to the increase in soil water content in these water harvesting techniques structures which led to better root development thereby increasing millet growth. The results obtained in the current study corroborate with those reported by Kouyaté *et al.* (2000) who reported that tied ridge increased sorghum height than ripping. The results also confirm the those reported by Fatondji (2002) who showed that zai increased millet growth in terms of height as compared to planting in flat.

The lowest plant height recorded under conventional tillage in the two cropping seasons could be due to low moisture availability. Application of manure or mineral P fertilizer during sowing period improved early development of pearl millet root which induced rapid growth of crop. Ayoola and Adeniyan (2006) reported that application of poultry manure and P fertilizers influenced plant growth and yield by providing more nutrients. The combination of organic manure and mineral fertilizer gave the best result in terms of pearl millet growth because of the quantity of nutrients made available to the soil- crop system during the growing stage. Rock phosphate and urea made nutrients directly available to the crop, while the organic manure released the nutrient slowly during the cropping period. The beneficial effects of combined organic manure and mineral fertilizers on cereal growth have previously been highlighted (Ouédraogo, 2004; Patel *et al.*, 2013).

4.3.2.2 Effects of water harvesting techniques and soil amendments on total dry matter production

Total dry matter of pearl millet was significantly ($P < 0.05$) enhanced by water harvesting techniques at elongation, 50 % flowering and maturity stages of growth in 2013. However, in 2014 water harvesting techniques did not significantly ($P > 0.05$) increase TDM (Table 4.4). This could be explained by the fact that water was not a limiting factor because the amount of water recorded was high and enough to satisfy crop requirement. The current result is in line with the earlier report by Zougmoré *et al.* (2014) who reported the potential of water harvesting techniques in increasing crop performance when the rainfall is limited.

Manure application increased total dry matter production at all stages of crop growth except at 50% flowering stage in 2014. The highest TDM (252.70 g $plant^{-1}$) was recorded under manure treatment at maturity, while the lowest (193.40 g $plant^{-1}$) was obtained by the control. This could be explained by increase of soil moisture in the root zone which improved nutrient uptake by the crop. This finding was consistent with the report of Fatondji (2002) that total dry matter increased with the use of zai. Moreover, manure application increased the total dry matter production by 32.57 % relative to the control. This could be due to increase in plant nutrients availability through the decomposition of manure and soil moisture retention effect of manure which led to rapid millet growth and consequently enhanced dry matter production.

Application of mineral fertilizer had a significant effect on millet total dry matter production. This could be attributed to the positive effect of mineral fertilizer in stimulating early root growth and enhancing plant nutrients availability which, consequently, improved biomass production. The present results are in agreement with the findings of Cooper *et al.* (1987) who showed that application of modest amounts of nitrogen and phosphorus fertilizers to soils is effective in increasing root development, and better dry matter production.

4.3.2.3 Effects of water harvesting techniques and soil amendments and their interaction on straw and grain yields

Pearl millet grain yield significantly increased on average by 57.00 and 42.00 % under zai and tied ridge, respectively compared to conventional tillage. Perhaps these results are due to the better soil moisture conservation and the availability of nutrients in the vicinity of millet rooting system in the water harvesting techniques in comparison with conventional tillage. The observed increases in grain yield following the use of zai compared favourably with the 32 % increase in grain yield of pearl millet reported by Fatondji (2002) in Niger but was lower than the 212 % increase in grain yield of sorghum reported by Wedum *et al.* (1996) in Mali. The increase in millet grain yield recorded by the use of tied ridge (42.00 % on average) was lower than that documented with zai. However, the increase in millet grain yield recorded in the current study was markedly higher than the 10.00 % increase in sorghum grain yield reported by Kouyaté *et al.* (2012) under tied ridge. Other reports indicated an increase of millet grain yield by 56.00 % under tied ridge compared to farmers' practice (Yoseph and Gebre, 2015). Yet, contrasting results were reported by

Kihara *et al.* (2012) who observed a decrease in yield of maize under tied ridge as a result of rainfall scarcity.

Manure application increased the millet grain yield by 44.66 % while the mineral fertilizer application increased grain yield by 48.68 and 59.31 % for 20.5 kg N: 23 kg P_2O_5 ha^{-1} and 41 kg N: 46 kg P_2O_5 ha^{-1} application rates, respectively compared to the control. Pearl millet performance under different soil amendment management options could be related to N and P availability to the crop and the manure quality. Similar result was obtained by Akponikpe *et al.* (2008) who reported that manure and crop residue application increased pearl millet yield by 95 % in Niger. Higher yield obtained under combined use of manure and mineral fertilizer could be attributed (apart from the supply of nutrient by both amendments) to the soil moisture improvement and also the micronutrient provided by to manure application (Zougmoré *et al*., 2003a; Arvind *et al*., 2006).

As productivity of most soils in their native state in the study area is very low (Bationo *et al.*, 1998), applying plant nutrients (compost, urea and NPK) to these poor soils induced great positive reaction to crop production, particularly during good rainfall years when soil moisture constraint is less (Zougmore *et al*., 2004). In plots with compost application, the mineralization of compost released not only the macro nutrients such as nitrogen and phosphorus but also considerable amounts of micronutrients for plant use (Zougmoré *et al.*, 2010)

Significant crop response to chemical fertilizer application in this study indicated the importance of fertilizer in the cropping system. Cropping system management should integrate appropriate water harvesting techniques, organic resources, even in small quantities, and the use of mineral fertilizers. This confirms the report by Vanlauwe *et al.*

(2011) who discovered greater agronomic performance when mineral fertilizer was combined with manure or compost.

4.3.2.4 Added benefit from combined use of water harvesting techniques and soil amendments on yield of pearl millet

The negative added benefits (antagonistic effect) under combined application of manure and mineral fertilizer could be attributed to the low nutrient utilization efficiencies and moisture stress at dry spell period. Similarly, Opoku (2011) found negative added benefit of cereals in Niger. Ouédraogo *et al.* (2007) reported an added benefit of -101 kg ha^{-1} following the combined application of sheep manure and urea and attributed the antagonistic effect to low nutrient utilization efficiency induced by moisture stress during grain filling. Mucheru *et al.* (2002) also found negative added benefits in the order of -150 to -250 kg ha^{-1} following the combined application of 30 kg N ha^{-1} of *Leucaena leucocephala* and 30 kg N ha^{-1} of mineral fertilizer. The antagonistic effect of *L. leucocephala* biomass and mineral fertilizer observed by these authors was however attributed to the high polyphenol content of the organic manure and its adverse effect on decomposition rate and N release. Moreover, the positive interaction between manure and mineral fertilizer at Sarauniya (Opoku, 2011), as indicated by the added benefits of 117 – 684 kg ha^{-1} was consistent with the body of evidence attesting to the profound synergism between organic and mineral fertilizers (Vanlauwe *et al.*, 2001).

4.3.2.5 Harvest Index

The HI, according to Smith and Hamel (2012), usually refers to the proportion of the total dry weight biomass (grain/biomass) in the harvest organs or the ability to mobilize photosynthates from stover (pod, straw) to seed (Polania *et al.*, 2015). Harvest Index, which reflects the efficiency of dry matter partitioning to the grain, is presented in Table 4.8. In the two cropping seasons, the HI was not significantly affected by different water harvesting techniques. Mahalakshmi and Bidinger (1985) found that water stress during flowering and grain filling reduced grain yields of both main shoot and tillers, making this the most sensitive stage. Fatondji (2002) reported that zai increased the harvest index mainly, a year characterized by intermittent dry spells that may have induced poor grain filling in contrast to a year with relatively better rainfall distribution.

In 2013 either manure and mineral fertilizer application significantly ($P < 0.05$) increased pearl millet HI. Similar result reported by Bekeko (2014) showed that farm yard manure and inorganic fertilizers either in sole or in combination could increase maize harvest index in eastern Ethiopia. According to Silva *et al.* (2006), manure application increased harvest index in two corn cultivars in Brazil. In 2014 soil amendment did not significantly ($P < 0.05$) increase pearl millet harvest index. The result accords with the findings of Zafar *et al.* (2012) who reported that application of different P inputs did not significantly increase harvest index.

4.3.2.6 Agronomic efficiency

Agronomic efficiency is defined as kilogramme crop yield increase per kilogramme nutrient applied. There was no significant effect of water harvesting techniques on agronomic N and P efficiencies in the two cropping seasons (Table 4.9). Contrarily, result reported by Fatondji (2002) showed that zai improved nutrient agronomic efficiency compared to planting on the flat. However, soil amendment treatments were significantly ($P < 0.001$) different in N and P agronomic efficiencies. A higher value of AE was recorded under treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} with 29.82 kg kg^{-1} N and 26.58 kg kg^{-1} P in 2014 that could be due to early availability and the efficient use of nutrients by crop. In this study, it was observed that the higher the rate of manure and mineral fertilizer applications, the lower the agronomic efficiency. Similarly, Efthimiadou *et al.* (2010) reported that agronomic efficiency was greater under low rates of mineral fertilizer than the high rates of mineral fertilizer. Also, Vanlauwe *et al.* (2011) reported that agronomic efficiency is low for excessive inorganic and organic fertilizer applications. The interaction among water harvesting techniques, organic manure and mineral fertilizer applications did not significantly ($P > 0.05$) influence agronomic efficiency. Fatondji *et al.* (2007) indicated that agronomic efficiency increased under 1000 kg of manure application and decreased with increase of manure rate.

4.4 Effect of water harvesting techniques and soil amendments on soil moisture content and rainwater use efficiency

4.4.1 Effects of water harvesting techniques and soil amendments on soil moisture content

4.4.1.1 Results

4.4.1.1.1 Effects of water harvesting techniques and soil amendments on soil gravimetric moisture content

The effects of water harvesting techniques and soil amendments on soil gravimetric moisture content are summarized in Table 4.10. Soil gravimetric moisture content was significantly ($P < 0.001$) affected under water harvesting techniques in the two cropping seasons. In 2014 the highest value was recorded under zai pit (13.91 %) at 0 – 20 cm depth while the lowest was obtained under conventional tillage (9.60 %) at 0 – 20 cm depth. The trend at 20 – 40 cm depth was zai > tied ridge > conventional tillage. Gravimetric moisture content increased from 0 – 20 cm to 20 - 40 cm depth except under conventional tillage.

In 2013 the use of manure significantly ($P < 0.001$) increased the gravimetric moisture content (8.59 %) at the 0 – 20 cm depth as compared to the control (7.72 %). However, there was no effect of manure application on the gravimetric moisture content of the subsoil (20 – 40 cm depth). Mineral fertilizer application also did not significantly ($P > 0.05$) influence soil gravimetric moisture content at both depths.

In 2014 manure treatment significantly ($P < 0.001$ and $P = 0.02$) increased soil moisture content by 12.99 and 13.79 % at 0 – 20 and 20 – 40 cm depths, respectively as compared to the control (10.34 and 11.05 %). Mineral fertilizer significantly ($P = 0.009$ and $P = 0.02$)

increased soil gravimetric moisture content. The trend was 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} = 0 kg N: 0 kg P_2O_5 ha^{-1} at 0 – 20 cm depth and 41 kg N: 46 kg P_2O_5 ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} > 0 kg N: 0 kg P_2O_5 ha^{-1} at 20 – 40 cm. The highest value was recorded by 41 kg N: 46 kg P_2O_5 ha^{-1} and the lowest by 0 kg N: 0 kg P_2O_5 ha^{-1}.

The interactive effect of water harvesting techniques and organic manure significantly (P = 0.01) influenced soil gravimetric moisture content at 0 – 20 cm and 20 – 40 cm depths, respectively in 2013 and 2014 (Table 4.11). The highest value was obtained under zai technique and the lowest under conventional tillage.

Table 4.10: Effects of water harvesting techniques and soil amendments on gravimetric moisture content at depth of 0 - 20 cm and 20 – 40 cm in 2013 and 2014 cropping seasons

Treatments	Moisture content (%)			
	2013		2014	
	0 – 20 cm	20 – 40 cm	0 – 20 cm	20 – 40 cm
Water harvesting techniques (A)				
Conventional tillage	7.28	8.85	9.60	9.50
Tied ridge	7.92	9.40	11.48	12.63
Zai	9.26	11.87	13.91	15.12
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	0.55	0.32	0.57	0.10
Organic manure (B) (kg ha^{-1})				
M0	7.72	9.85	10.34	11.05
M 2500	8.59	10.22	12.99	13.79
Fpr	< 0.001	0.20	< 0.001	0.02
Lsd (0.05)	0.45	ns	0.46	0.81
Mineral fertilizer (C) (kg ha^{-1})				
0 N: 0 P_2O_5	8.24	10.33	11.17	11.05
20.5 N: 23 P_2O_5	8.06	9.76	11.74	12.59
41 N: 46 P_2O_5	8.16	10.02	12.08	13.06
Fpr	0.55	0.28	0.009	0.02
Lsd (0.05)	ns	ns	0.57	0.10
Int A x B	0.01	ns	ns	0.05
Int A x C	ns	ns	ns	ns
Int B x C	ns	ns	ns	ns
Int A x B x C	ns	ns	ns	ns
CV (%)	19.90	16.70	11.40	18.20

In: Interaction, ns: not significant at F probability 5 %

Table 4.11: Interactive effect of water harvesting techniques and manure on soil gravimetric moisture content in 2013 and 2014 cropping seasons

Water harvesting techniques	Manure (kg ha-1)	Soil moisture content (%)	
		0 -20 cm 2013	20 - 40 cm 2014
C. tillage	M0	7.06	8.45
	M 2500	7.51	10.55
Tied ridge	M0	7.77	11.18
	M 2500	8.06	14.08
Zai	M0	8.34	13.51
	M 2500	10.19	16.73
	Fpr	0.01	0.05
	Lsd (0.05)	1.63	1.41

C. tillage: Conventional tillage

4.4.1.1.2 Effects of water harvesting techniques and soil amendments on soil moisture storage

Results on soil moisture storage are presented in Table 4.12. Soil moisture storage was significantly ($P < 0.05$) affected by water harvesting techniques in 2014 cropping season. The use of zai pit led to significantly higher soil moisture storage at the 20 – 40 cm depth at 45 and 90 days after sowing. Conventional tillage on the other hand led to the lowest soil moisture storage.

Manure application significantly ($P < 0.001$) influenced the soil moisture storage at both depths and sampling days compared to the control. The highest value was 50.98 mm at 20 – 40 cm depth at 45 days after sowing. Soil moisture storage was also significantly (P

< 0.05) high at the 20 – 40 cm and 0 – 20 cm depths at 45 and 90 days, respectively on mineral fertilizer plots. The highest value obtained (46.32 mm) was at 20 – 40 cm depth at 45 days.

The combined effect of water harvesting techniques and manure application increased the soil moisture storage at the 0 - 20 cm at 45 days after sowing (Table 4.13). A significant interactive effect between manure and mineral fertilizer applications also led to increase in the soil moisture storage at both the 0 – 20 and 20 – 40 cm depths at 45 days after sowing (Table 4.14). At 90 days after sowing, however, only the moisture stored at the 0 – 20 cm was affected by the combined effect of manure and mineral fertilizer.

Table 4.12: Effects of water harvesting techniques and soil amendments on soil moisture storage in 2014 cropping season

Treatments	Soil moisture storage (mm)			
	0 – 20 cm	20 – 40 cm	0 – 20 cm	20 – 40 cm
	45 days		90 days	
Water harvesting techniques (A)				
Conventional tillage	39.62	39.48	19.16	13.7
Tied ridge	39.34	47.16	20.42	22.14
Zai	45.08	52.06	31.48	25.92
Fpr	0.005	0.040	0.003	0.040
Lsd (0.05)	2.42	9.08	4.38	8.78
Organic manure (B) (kg ha^{-1})				
M0	36.98	41.48	15.02	13.44
M 2500	45.72	50.98	32.34	27.72
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	2.76	2.60	2.42	3.40
Mineral fertlizer (C) (kg ha^{-1})				
0 N: 0 P_2O_5	42.24	43.88	20.36	20.04
20.5 N: 23 P_2O_5	39.02	48.52	24.98	20.86
41 N: 46 P_2O_5	42.78	46.32	25.7	20.84
Fpr	0.06	0.02	0.002	0.90
Lsd (0.05)	ns	3.2	2.96	ns
Int A x B	0.04	ns	ns	ns
Int A x C	ns	ns	ns	ns
Int B x C	`< 0.001	0.001	0.040	ns
Int A x B x C	ns	ns	ns	ns

CV (%)	12.00	10.10	18.40	29.80

Int: interaction, ns: not significant at F probability 5 %

Table 4.13: Interactive effect of water harvesting techniques and organic manure on soil moisture storage at 45 days (0 - 20 cm depth) in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	soil moisture storage (mm) 45 days (0 -20 cm)
Conventional tillage	M0	32.74
	M 2500	46.52
Tied ridge	M0	35.66
	M 2500	43
Zai	M0	42.54
	M 2500	47.62
	Fpr	0.04
	Lsd (0.05)	3.84

Table 4.14: Interactive effect between manure and mineral fertilizer at 45 and 90 days (0 – 20 and 20 – 40 cm depth) on soil moisture storage in 2014 cropping season

(kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	soil moisture storage (mm) 45 days 0 – 20 cm	45 days 20 - 40 cm	90 days 0 - 20 cm
M0	0 N: 0 P_2O_5	33.88	35.44	9.44
	20.5 N: 23 P_2O_5	33.94	45.34	17.38
	41 N: 46 P_2O_5	43.12	43.68	18.26
M 2500	0 N: 0 P_2O_5	50.6	52.32	31.28
	20.5 N: 23 P_2O_5	44.08	51.68	32.58
	41 N: 46 P_2O_5	42.44	48.96	33.14

Fpr	< 0.001	0.001	0.04
Lsd (0.05)	4.80	4.52	4.20

Manure

4.4.1.1.3 Effects of water harvesting techniques and soil amendments on bulk density of soil

Conventional tillage had the highest bulk density in the two depths and days of sampling whilst the lowest bulk density was recorded by the tied ridge. Manure treatment had lower bulk density as compared to the control. A higher value recorded under the control was 1.49 g cm^{-3} at 20 - 40 cm depth 90 days after sowing. Mineral fertilizer also significantly (P = 0.006) affected bulk density at the two depths at 45 days after sowing (Table 4.15).

The combined effect of water harvesting techniques and manure application significantly decreased the bulk density of the subsoil at 90 days after sowing (Appendix 6). The combined use of conventional tillage without manure application recorded the highest bulk density (1.55 g cm^{-3}) while the zai with manure application obtained the lowest value (1.26 g cm^{-3}).

Table 4.15: Effects of water harvesting techniques and soil amendments on soil bulk density in 2014 cropping season

Treatments	Bulk density ($g\ cm^{-3}$) in 2014			
	45 days	45 days	90 days	90 days
	0 – 20 cm	20 – 40 cm	0 – 20 cm	20 – 40 cm
Water harvesting techniques (A)				
Conventional tillage	1.52	1.50	1.51	1.52
Tied ridge	1.35	1.33	1.45	1.45
Zai	1.35	1.33	1.46	1.35
Fpr	0.028	0.027	0.460	0.280
Lsd (0.05)	0.12	0.13	ns	ns
Organic manure (B) ($kg\ ha^{-1}$)				
M0	1.47	1.45	1.48	1.49
M 2500	1.35	1.33	1.46	1.39
Fpr	< 0.001	< 0.001	0.270	< 0.001
Lsd (0.05)	0.045	0.045	ns	0.04
Mineral fertilizer (C) ($kg\ ha^{-1}$)				
0 N: 0 P_2O_5	1.46	1.44	1.49	1.48

20.5 N: 23 P_2O_5	1.41	1.39	1.48	1.44
41 N: 46 P_2O_5	1.36	1.34	1.46	1.39
Fpr	0.006	0.006	0.430	0.003
Lsd (0.05)	0.05	0.056	ns	0.04
Int A x B	ns	ns	ns	0.028
Int A x C	ns	ns	ns	ns
Int B x C	ns	ns	ns	ns
Int A x B x C	ns	ns	ns	ns
CV (%)	5.80	5.90	5.00	5.10

Int: interaction, ns: not significant at F probability 5 %

4.4.1.2 Discussion

4.4.1.2.1 Effects of water harvesting techniques and soil amendments on soil gravimetric moisture content

Gravimetric moisture content was significantly ($P < 0.001$) higher under water harvesting techniques notably in the second year of the experiment (2014) which could be attributed to the increase in rainwater stored during this period. Zougmoré *et al.* (2003a) observed an increase in soil water content under tied ridge practice up to 20 % compared to the conventional tillage practice because of the high total porosity as a result of low bulk density induced by soil structure disturbance caused by tillage.

The mean soil moisture content over the 14 weeks measurement in the top and sub soil corresponded with the trend of zai > tied ridge > conventional tillage. Parvin (2012) had reported a similar result that the water content increased with depth. The higher moisture could be due to manure only or combined with mineral fertilizer applied under the zai and tied ridge treatments. The organic manure retained water and could conserve soil moisture through soil structure improvement.

On the sandy loam soils in the experimental area, emphasis must be placed on optimizing soil moisture storage during the peak periods of rainfall. Beyond this period, any incidence of reduced rainfall results in a drastic depletion of available soil moisture in the rooting zone for sustainable crop production.

4.4.1.2.2 Effects of water harvesting techniques and soil amendments on soil moisture storage

The source of water for the growth, development and yield of crops in rainfed agriculture is rainfall (Mweso, 2003). Rainfall in the study area is erratic and a major limiting factor for arable crop production and therefore any soil management practice adopted must create favourable soil conditions for effective water conservation in order to meet crop requirements. Soil moisture is highly critical in ensuring good and uniform seed germination and seedling emergence (Arsyid *et al.*, 2009), crop growth and yield. The condition implies that in-situ moisture conservation which is a necessity to sustaining high crop growth and yield, particularly in rainfed agriculture must be optimized as similarly reported by Adama (2003).

The soil moisture storage at 45 and 90 days after sowing at the 0 – 20 cm depth ranged from 20.42 to 39.34 mm under tied ridge and 31.48 to 45.08 mm under zai. The soil moisture stored at 45 and 90 days after sowing at 20 – 40 cm depth ranged from 25.92 to 52.06 mm under zai and 22.14 to 47.16 mm under tied ridge.

Soil moisture was higher under zai and tied ridge as compared to conventional tillage. The higher soil moisture stored under zai at 45 days after sowing can be attributed to the higher rainfall recorded during this period. It could further be explained also by the amount of rainwater stored in the pit. The higher impact of zai on moisture stored could be attributed to the low soil disturbance and soil compaction under zai technique. However, the soil moisture stored decreased at 90 days after sowing corresponding to the decrease in amount of rainfall. Soil moisture storage is affected by tillage practices as observed by Zougmoré *et al.* (2004). Zai technique promotes water collection and therefore increases the soil water content in root zone (Roose *et al.*, 1993).

Furthermore, higher water stored under the tied ridge than conventional tillage could be due to design of the former which allowed higher water capture and retention than the fairly flat surface under the latter (with little potential for water capturing). Similar results was reported by Motsi *et al.* (2004) who showed that tied ridge conserved better soil moisture than conventional tillage. In Ethiopia, Yoseph and Gebre (2015) reported that tied ridge is the best practice for moisture conservation for increased crop productivity.

The higher moisture stored under zai with manure at 45 days could be explained by the fact that the manure in the seed hole might have contributed to retaining rainwater captured by the pit, and thus reduced moisture loss...The combined use of tied ridge and manure also improved soil moisture stored at 45 days at the 0 – 20 cm depth compared to tied ridge alone. This suggests a complementary effect of manure with the tillage practice on moisture stored. According to Chepkemoi (2014), tied ridge with application of farmyard manure and Minjingu rock phosphate was more efficient for moisture conservation (6.73 %) than the oxen ploughing (3.2 %).

The combined effect of manure and mineral fertilizer significantly ($P < 0.05$) increased soil moisture storage. The highest soil moisture storage was recorded under the manuring treatment at the 0 – 20 and 20 – 40 cm depths at 45 days after sowing could be explained by improvement in soil structure, retention of water and enhancement of water holding capacity. Similar results reported by Stoffella *et al.* (1997) showed that manure has multiple benefits in improvement of soil structure and moisture storage.

4.4.1.2.3 Effects of water harvesting techniques and soil amendments on soil bulk density

Soil bulk density is the most frequently measured soil quality parameter in tillage experiments (Rasmussen, 1999) and has an influence on the various physical, chemical and biological processes in the soil. It is a dynamic soil property which is susceptible to change in time and also gives an indication of the soil strength. Conventional tillage exerted greater effect on the bulk density of both the top and sub soil than the zai and tied ridge. Similarly, Roscoe and Buurman (2003) showed greater bulk density values under conventional tillage systems when compared to no-tillage. In contrast, the findings of Chaplain *et al.* (2011) indicated increases in soil bulk density under tied ridging while no such increases were found under the no tillage practice. The observation that bulk density was low under zai and tied ridge affirmed the assertion of Meek *et al.* (1992) that water harvesting techniques could loosen the soil to reduce bulk density and provide a favourable bio - physical condition for seedling emergence, crop growth and yield.

4.4.2 Rainwater use efficiency

4.4.2.1 Results

There were significant ($P = 0.004$ and $P < 0.001$) differences in rainwater use efficiency (RWUE) among the water harvesting techniques in both cropping seasons (Table 4.16). In the first year, a higher value (2.46 kg grain mm^{-1}) was recorded under zai and a lower value (1.67 kg grain mm^{-1}) was obtained under conventional tillage. In the second year a higher value (3.45 kg grain mm^{-1}) was obtained under zai and a lower value (2.06 kg grain mm^{-1}) was reported under conventional tillage. The trend of rainwater use efficiency was zai > tied ridge > conventional tillage.

Rainwater use efficiency was significantly ($P < 0.001$) affected by soil amendment management options. Manure application increased rainwater use efficiency by 33 – 50 % over the control in 2013 and 2014. The treatment 41 kg N: 46 kg P_2O_5 ha^{-1} (3.20 kg grain mm^{-1}) was the best mineral fertilizer as compared to the control. The combined application of manure and mineral fertilizer significantly ($P < 0.001$ and $P = 0.046$) affected the rainwater use efficiency in both years. The highest RWUE value recorded was 3.45 kg grain mm^{-1} with the treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} (Table 4.17).

Table 4.16: Effects of water harvesting techniques and soil amendments on rainwater use efficiency in 2013 and 2014 cropping seasons

Treatments	Rainwater use efficiency (kg grain mm^{-1})	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	1.67	2.06
Tied ridge	2.20	3.17
Zai	2.46	3.45
Fpr	0.004	< 0.001
Lsd (0.05)	0.29	0.27
Organic manure (B) (kg ha^{-1})		
M0	1.67	2.48
M 2500	2.50	3.30
Fpr	< 0.001	< 0.001
Lsd (0.05)	0.21	0.30

Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	1.55	2.37
20.5 N: 23 P_2O_5	2.31	3.12
41 N: 46 P_2O_5	2.47	3.20
Fpr	< 0.001	< 0.001
Lsd (0.05)	0.26	0.37
Int A x B	ns	ns
Int A x C	ns	ns
Int B x C	< 0.001	0.046
Int A x B x C	ns	ns
CV (%)	18.10	18.70

Int: Interaction, ns: not significant at F probability 5 %

Table 4.17: Interactive effect of organic manure and mineral fertilizer on rainwater use efficiency in 2013 and 2014 cropping seasons

Manure	Mineral fertilizer	Rainwater use efficiency (kg grain mm^{-1})	
(kg ha^{-1})	(kg ha^{-1})	2013	2014
M0	0 N: 0 P_2O_5	0.93	1.69
	20.5 N: 23 P_2O_5	2.24	2.79
	41 N: 46 P_2O_5	2.01	2.97
M 2500	0 N: 0 P_2O_5	2.18	3.04
	20.5 N: 23 P_2O_5	2.38	3.45
	41 N: 46 P_2O_5	2.94	3.42
	Fpr	< 0.001	0.046

Lsd (0.05)	0.37	0.52

4.4.2.2 Discussion

The low amount and uneven distribution of rainfall at the study area (Figure 3.3 and 3.4) is a recipe for low yield of pearl millet. Therefore the combination of better water management practices with nutrient supply (from manure and mineral fertilizer) tends to increase water capture and decrease unproductive evaporation with the resultant effect of increased straw and grain yield. The higher values of rainwater use efficiency obtained under zai and tied ridge could be attributed to the increase in availability of water in these water harvesting structures. In Niger, Fatondji (2002) showed that zai pit improved pearl millet water use efficiency. Similarly, in Nigeria, Chiroma *et al.* (2008) reported that tied ridge increased water use efficiency by 35 % as compared with flat bed. Increase in crop water use efficiency increases grain yield (Fatondji, 2002).

Manure and mineral fertilizer significantly ($P < 0.001$) affected rainwater use efficiency with the latter recording the higher values of rainwater use efficiency and yield. This could be due to the availability of more water and readily available nutrient from mineral fertilizer that might have enhanced biomass production and grain yield. Hatfield *et al.* (2001) found that soil nutrient management options improved water use by 15 to 25 % over the control. Similar results reported by Payne *et al.* (1995) showed that in low-P soils, addition of P fertilizer increased the dry matter yield and RWUE of pearl millet. The finding of this study suggests that, soil nutrient status and water availabily are key determinants of biomass and grain production of pearl millet in West africa. According to (Payne, 1997), the water use efficiency of Pearl millet [*Pennisetum glaucum* (L.) R. was improved through the combination of N and organic manure management. The interactive effect of manure and mineral fertilizer applications significantly ($P < 0.05$) increased rainwater use efficiency. This could be explained by the complementary effect of manure and mineral fertilizer which leads to the production of higher grain yield.

4.5 Effects of water harvesting techniques and soil amendments on soil chemical properties

4.5.1 Results

4.5.1.1 Effects of water harvesting techniques and soil amendments on soil pH

The effects of water harvesting techniques and soil amendment management options on soil pH at 0 – 20 cm soil depth are presented in Table 4.18. Soil pH under pearl millet was significantly ($P = 0.028$ and $P = 0.046$) affected by water harvesting techniques in the two cropping seasons. The soil pH ranged from 5.50 to 5.90 with a decreasing trend of zai = tied ridge > conventional tillage, respectively in 2013 and 2014 cropping seasons. In addition, manure significantly ($P < 0.001$ and $P = 0.007$) influenced soil pH under pearl millet cropping system while mineral fertilizer did not affect the soil pH. The manure recorded the highest soil pH of 5.90 to 5.95 while the control had the lowest soil pH of 5.61 to 5.64, respectively for 2013 and 2014.

On the other hand, the combined effect of water harvesting techniques and mineral fertilizer significantly ($P = 0.04$) increased soil pH (Table 4.19). The highest value was recorded under zai and 41 kg N: 46 kg P_2O_5 ha^{-1} treatment with pH = 6.26 whilst the lowest value was obtained under interaction between conventional tillage and 0 kg N: 0

kg P_2O_5 ha^{-1} (pH = 5.41). The combined effect of manure and mineral fertilizer applications increased soil pH (Table 4.20). The highest value was recorded under manure application at 2500 kg ha^{-1} and 0 kg N: 0 kg P_2O_5 ha^{-1} (pH = 6.06) while the lowest value was obtained under 0 kg of manure and 0 kg N: 0 kg P_2O_5 ha^{-1} (pH = 5.22).

Table 4.18: Effects of water harvesting techniques and soil amendments on soil pH in 2013 and 2014 cropping seasons

Treatments	pH (1:1 soil:water)	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	5.50	5.66
Tied ridge	5.86	5.75
Zai	5.95	5.93
Fpr	0.028	0.046
Lsd (0.05)	0.30	0.20
Organic manure (B) (kg ha^{-1})		
M0	5.64	5.61

M 2500	5.90	5.95
Fpr	< 0.001	0.007
Lsd (0.05)	0.08	0.24
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	5.72	5.64
20.5 N: 23 P_2O_5	5.81	5.84
41 N: 46 P_2O_5	5.78	5.86
Fpr	0.17	0.25
Lsd (0.05)	ns	ns
Int A x B	ns	ns
Int A x C	ns	0.04
Int B x C	ns	0.008
Int A x B x C	ns	ns
CV (%)	12.40	7.40

Int: Interaction, ns: not significant at F probability 5 %

Table 4.19: Interactive effect of water harvesting techniques and mineral fertilizer on soil pH in 2014 cropping season

Water harvesting Techniques	Mineral fertilizer (kg ha^{-1})	pH (1:1 soil:water)
C. tillage	0 N: 0 P_2O_5	5.41
	20.5 N: 23 P_2O_5	5.70
	41 N: 46 P_2O_5	5.88
Tied ridge	0 N: 0 P_2O_5	5.89
	20.5 N: 23 P_2O_5	5.90
	41 N: 46 P_2O_5	5.46
Zai	0 N: 0 P_2O_5	5.63

20.5 N: 23 P_2O_5	5.92
41 N: 46 P_2O_5	6.26
Fpr	0.04
Lsd (0.05)	0.43

C. tillage: Conventional tillage

Table 4.20: Interactive effect of organic manure and mineral fertilizer on soil pH in 2014 cropping season

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	pH (1:1 soil:water)
M0	0 N: 0 P_2O_5	5.22
	20.5 N: 23 P_2O_5	5.90
	41 N: 46 P_2O_5	5.72
M 2500	0 N: 0 P_2O_5	6.06
	20.5 N: 23 P_2O_5	5.78
	41 N: 46 P_2O_5	6.01
	Fpr	0.008
	Lsd (0.05)	0.40

4.5.1.2 Effects of water harvesting techniques and soil amendments on soil available phosphorus

In the first cropping season, available phosphorus content was not influenced ($P > 0.05$) by water harvesting techniques. The values ranged from 4.94 to 5.90 mg kg^{-1} in the order of zai = tied ridge = conventional tillage (Table 4.21). The manure treatment significantly ($P = 0.002$) increased available P content under pearl millet. The lower and higher rates of mineral fertilizer treatments significantly ($P < 0.001$) increased and decreased the available P content, respectively in 2013.

In the second cropping season, available P content was significantly (P = 0.003) increased the zai technique producing significantly greater effect than the tied ridge treatment. The available P content in the soil was significantly enhanced by manuring. Contrary to 2013 cropping season, the available P content was significantly ($P < 0.001$) impacted by increasing rate of fertilization.

In the 2014 cropping season, the interactive effects of water harvesting techniques and mineral fertilizer application significantly ($P < 0.05$) and positively influenced soil available P content (Tables 4.22). In 2013 crpopping season, only water harvesting techniques and mineral fertilizer positively interacted to increase the available P content. The conventional tillage with 41 kg N: 46 kg P_2O_5 ha^{-1} caused a higlly significant decreased in the available P content in 2013 cropping season. In 2014 the interactive effects on available P obtained were 22.8, 41.41.2 and 261.9% higher than in 2013 for the control, lowest and highest fertilizer rates, respectively under conventional tillage. The results produced under tied ridge and zai combined with fertilization followed similar trend as reported for the conventional tillage.

Table 4.23 shows interactive effects of water harvesting techniques and combined manure and mineral fertilizer applications on soil available phosphorus content. The highest available P content was obtained with the use of zai, manure at 2500 kg ha^{-1} and of mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} (27.71 mg kg^{-1}), while the lowest value was obtained from the combined use of conventional tillage, manure at 0 kg and of mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} (3.35 mg kg^{-1}). In the second cropping season, combined use of water harvesting techniques and manure application significantly influenced available phosphorus content (Appendix 7). Zai and manure application at

2500 kg ha^{-1} produced the highest available phosphorus (19.69 mg kg^{-1}), while the conventional tillage and 0 kg of manure recorded the lowest available P (7.05 mg kg^{-1}). Interactive effects of manure and mineral fertilizer applications also affected available phosphorus content (Appendix 8). The application of manure at 2500 kg ha^{-1} with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} led to the highest available P content.

Table 4.21: Effects of water harvesting techniques and soil amendments on available phosphorus in 2013 and 2014 cropping seasons

Treatments	Available phosphorus (mg kg^{-1})	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	4.94	9.49
Tied ridge	5.83	10.42
Zai	5.90	13.91
Fpr	0.220	0.003
Lsd (0.05)	ns	1.61

Organic manure (B) (kg ha^{-1})		
M0	4.98	8.50
M 2500	6.13	14.40
Fpr	0.002	0.001
Lsd (0.05)	0.68	1.17
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	4.57	5.90
20.5 N: 23 P_2O_5	6.46	12.34
41 N: 46 P_2O_5	5.64	15.58
Fpr	< 0.001	< 0.001
Lsd (0.05)	0.83	1.43
Int A x B	ns	< 0.001
Int A x C	0.008	< 0.001
Int B x C	ns	< 0.001
Int A x B x C	ns	< 0.001
CV (%)	21.90	18.70

Int: Interaction, ns: not significant at F probability 5 %

Table 4.22: Interactive effect of water harvesting techniques and mineral fertilizer on available phosphorus content in 2013 and 2014 cropping seasons

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	Available phosphorus (mg kg^{-1}) 2013	2014
C. tillage	0 N: 0 P_2O_5	4.73	5.81
	20.5 N: 23 P_2O_5	6.28	8.87
	41 N: 46 P_2O_5	3.81	13.79

Tied ridge	0 N: 0 P_2O_5	4.61	6.13
	20.5 N: 23 P_2O_5	6.02	10.39
	41 N: 46 P_2O_5	6.87	14.75
Zai	0 N: 0 P_2O_5	4.36	5.77
	20.5 N: 23 P_2O_5	7.09	17.75
	41 N: 46 P_2O_5	6.25	18.21
	Fpr	0.008	< 0.001
	Lsd (0.05)	1.62	2.34

C. tillage: Conventional tillage

Table 4.23: Interactive effects of water harvesting techniques, manure and mineral fertilizer on available phosphorus in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	ıble phosphorus (mg kg^{-1})
C. tillage	M0	0 N: 0 P_2O_5	5.88
		20.5 N: 23 P_2O_5	11.91
		41 N: 46 P_2O_5	3.35
	M 2500	0 N: 0 P_2O_5	5.73

		20.5 N: 23 P_2O_5	5.83
		41 N: 46 P_2O_5	24.23
Tied ridge	M0	0 N: 0 P_2O_5	7.30
		20.5 N: 23 P_2O_5	7.21
		41 N: 46 P_2O_5	16.48
	M 2500	0 N: 0 P_2O_5	4.96
		20.5 N: 23 P_2O_5	13.56
		41 N: 46 P_2O_5	13.02
Zai	M0	0 N: 0 P_2O_5	6.31
		20.5 N: 23 P_2O_5	7.79
		41 N: 46 P_2O_5	10.30
	M 2500	0 N: 0 P_2O_5	5.24
		20.5 N: 23 P_2O_5	27.71
		41 N: 46 P_2O_5	26.11
		Fpr	< 0.001
		Lsd (0.05)	3.40

C. tillage: Conventional tillage

4.5.1.3 Effects of water harvesting techniques and soil amendments on soil total nitrogen

Data in Table 4.24 show that water harvesting techniques did not significantly ($P > 0.05$) affect the soil total nitrogen content in the two years of the experiment. Total N contents ranged from 0.019 to 0.022 % in 2013 and 0.028 to 0.034 % in 2014. In the first cropping season, manure application significantly ($P = 0.041$) influenced soil total N content but in the second cropping season it did not. In both cropping seasons, the mineral fertilizer application did not affect total N content.

In the second cropping season, the interactive effects of water harvesting techniques, manure and mineral fertilizer applications significantly ($P < 0.05$) affected the total nitrogen content (Table 4.25). The highest total nitrogen content was found with the use of zai, manure at 2500 kg ha^{-1} and of mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} (0.038 %). Also, combined application of manure and mineral fertilizer influenced the total N content (Appendix 9). The application of manure at 2500 kg ha^{-1} with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} produced the highest total nitrogen content, while the mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} gave the lowest value.

Table 4.24: Effects of water harvesting techniques and soil amendments on soil total nitrogen in 2013 and 2014 cropping seasons

Treatments	Total nitrogen (%)	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	0.020	0.028
Tied ridge	0.022	0.031

Zai	0.019	0.034
Fpr	0.930	0.180
Lsd (0.05)	ns	ns
Organic manure (B) (kg ha^{-1})		
M0	0.018	0.030
M 2500	0.023	0.032
Fpr	0.041	0.420
Lsd (0.05)	0.004	ns
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	0.019	0.029
20.5 N: 23 P_2O_5	0.020	0.032
41 N: 46 P_2O_5	0.020	0.031
Fpr	0.800	0.600
Lsd (0.05)	ns	ns
Int A x B	ns	ns
Int A x C	ns	ns
Int B x C	ns	0.002
Int A x B x C	ns	0.013
CV (%)	37.60	26.80

Int: interaction, ns: not significant at F probability 5 %

Table 4.25: Interactive effects of water harvesting techniques, manure and mineral fertilizer on soil total nitrogen in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Total nitrogen (%)
C. tillage	M0	0 N: 0 P_2O_5	0.030

		20.5 N: 23 P_2O_5	0.027
		41 N: 46 P_2O_5	0.027
	M 2500	0 N: 0 P_2O_5	0.030
		20.5 N: 23 P_2O_5	0.030
		41 N: 46 P_2O_5	0.023
Tied ridge	M0	0 N: 0 P_2O_5	0.037
		20.5 N: 23 P_2O_5	0.030
		41 N: 46 P_2O_5	0.027
	M 2500	0 N: 0 P_2O_5	0.027
		20.5 N: 23 P_2O_5	0.027
		41 N: 46 P_2O_5	0.037
Zai	M0	0 N: 0 P_2O_5	0.033
		20.5 N: 23 P_2O_5	0.040
		41 N: 46 P_2O_5	0.020
	M 2500	0 N: 0 P_2O_5	0.020
		20.5 N: 23 P_2O_5	0.040
		41 N: 46 P_2O_5	0.053
		Fpr	0.013
		Lsd (0.05)	0.014

C. tillage: Conventional tillage

4.5.1.4 Effects of water harvesting techniques and soil amendments on soil organic carbon

Water harvesting techniques did not significantly ($P > 0.05$) affect soil organic carbon content during the first year of experiment. However, it significantly ($P = 0.01$) influenced soil organic carbon in the second year (Table 4.26). A higher value of soil organic carbon was recorded under tied ridge (0.45 %) followed by zai (0.40 %) and lower value was obtained under conventional tillage (0.30 %).

Furthermore, manure and mineral fertilizer treatments did not significantly (P > 0.05) affect soil organic carbon content in the first year of experiment but in the second year the soil organic carbon content was significantly (P = 0.003) increased The manure treatment yielded higher in soil organic carbon content (0.41 %) as compared to the control (0.35 %). In 2014 the trend for mineral fertilizer was 20.5 kg N: 23 kg P_2O_5 ha^{-1} (0.43 %) > 0 kg N: 0 kg P_2O_5 ha^{-1} (0.37 %) = 41 kg N: 46 kg P_2O_5 ha^{-1} (0.36 %).

The interactive effects of either zai or tied ridge treatment water harvesting techniques and manure application significantly (P < 0.05) enhanced soil organic carbon in 2014 cropping season (Table 4.27) with the highest value recorded under tied ridge treatment, while the lowest value was obtained under conventional tillage.

Table 4.26: Effects of water harvesting techniques and soil amendments on soil organic carbon in 2013 and 2014 cropping seasons

Treatments	Soil organic carbon (%)	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	0.38	0.30
Tied ridge	0.40	0.45

Zai	0.40	0.40
Fpr	0.970	0.003
Lsd (0.05)	ns	0.08
Organic manure (B) (kg ha^{-1})		
M0	0.37	0.35
M 2500	0.42	0.41
Fpr	0.170	0.003
Lsd (0.05)	ns	0.04
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	0.40	0.37
20.5 N: 23 P_2O_5	0.41	0.43
41 N: 46 P_2O_5	0.37	0.36
Fpr	0.630	0.006
Lsd (0.05)	ns	0.04
Int A x B	ns	0.003
Int A x C	ns	ns
Int B x C	ns	ns
Int A x B x C	ns	ns
CV (%)	31.10	17.30

Int: Interaction, ns: not significant at F probability 5 %

Table 4.27: Interactive effect of water harvesting techniques and manure on soil organic carbon in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Soil organic carbon (%)
C. tillage	M0	0.32

	M 2500	0.29
Tied ridge	M0	0.40
	M 2500	0.49
Zai	M0	0.34
	M 2500	0.47
	Fpr	0.003
	Lsd (0.05)	0.06

C. tillage: Conventional tillage

4.5.1.5 Effects of water harvesting techniques and soil amendments on soil exchangeable potassium

Water harvesting techniques did not significantly ($P > 0.05$) impact on exchangeable potassium under pearl millet cropping system. Amount of total exchangeable potassium decreased from the first to the second cropping season (Table 4.28).

The manure application did not ($P > 0.05$) increased exchangeable K content in the first year of experiment but in the second year manure slightly ($P < 0.05$) changed exchangeable potassium content. A higher value was obtained from manure treatment (0.055 $cmol_c$ kg^{-1}) as compared to the control (0.050 $cmol_c$ kg^{-1}). Mineral fertilizer in the two years of experiment significantly ($P = 0.002$ and $P = 0.006$) impacted on exchangeable potassium content.

The interactive effects of water harvesting techniques and manure application significantly ($P < 0.05$) affected exchangeable potassium content of the soil in 2014 (Appendix 10). The highest value was obtained under tied ridge and manure application at 2500 kg ha^{-1} (0.62 $cmol_c$ kg^{-1}), while the lowest value was found under tied ridge and 0 kg of manure

(0.044 $cmol_c$ kg^{-1}). The interactive effects between water harvesting techniques and mineral fertilizer application exerted significant impact on the soil exchangeable K content (Appendix 11). The highest value was recorded under zai with 20.5 kg N: 23 kg P_2O_5 ha^{-1} while the lowest was obtained under conventional tillage without mineral fertilizer application. Also, the combined application of manure and mineral fertilizer significantly (P = 0.033) influenced the exchangeable potassium content of the soil (Appendix 12). The use of manure at 2500 kg ha^{-1} with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} or 20.5 kg N: 23 kg P_2O_5 ha^{-1} gave signicantly higher exchangeable K content than without manure application.

Table 4.28: Effects of water harvesting techniques and soil amendments on soil exchangeable potassium content in 2013 and 2014 cropping seasons

Treatments	Exchangeable K ($cmol_c$ kg^{-1})	
	2013	2014

Water harvesting techniques (A)		
Conventional tillage	0.150	0.050
Tied ridge	0.130	0.050
Zai	0.140	0.060
Fpr	0.400	0.470
Lsd (0.05)	ns	ns
Organic manure (B) (kg ha^{-1})		
M0	0.120	0.050
M 2500	0.160	0.055
Fpr	0.450	0.030
Lsd (0.05)	ns	0.005
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	0.140	0.047
20.5 N: 23 P_2O_5	0.150	0.055
41 N: 46 P_2O_5	0.130	0.055
Fpr	0.002	0.006
Lsd (0.05)	0.030	0.006
Int A x B	ns	0.002
Int A x C	ns	< 0.001
Int B x C	ns	0.033
Int A x B x C	ns	ns
CV (%)	27.90	16.30

Int: Interaction, ns: not significant at F probability 5 %

4.5.1.6 Effects of water harvesting techniques and soil amendments on cation exchange capacity

Table 4.29 shows the effect of water harvesting techniques and soil amendments on cation exchange capacity (CEC). Water harvesting techniques in both cropping seasons did not significantly ($P > 0.05$) affect the CEC of the soil. The highest value of CEC was recorded under zai while the lowest was obtained under conventional tillage.

Manuring significantly ($P = 0.01$, $P < 0.001$) improved CEC in the both year of experiment. The mineral fertilizer in the two years of experiment significantly ($P = 0.04$ and $P = 0.02$) enhanced the cation exchange capacity. A higher value was recorded under mineral fertilizer application at 41 kg N: 46 kg P_2O_5 ha^{-1} (6.62 $cmol_c$ kg^{-1}).

The combined application of manure and mineral fertilizer in the second year affected soil CEC (Table 4.30). A higher value was recorded under 2500 kg of manure and 20.5 kg N: 23 kg P_2O_5 ha^{-1} (6.55 $cmol_c$ kg^{-1}) but the value decreased as the doubled rate of the mineral fertlizer. Interactive effects of water harvesting techniques and mineral fertilizer application in the two years impacted on soil CEC in both cropping seasons (Appendix 13). The combined use of zai with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} gave the highest CEC value (7.78 $cmol_c$ kg^{-1}), while conventional tillage without mineral fertilizer application gave the lowest value (4.70 $cmol_c$ kg^{-1}).

Table 4.29: Effects of water harvesting techniques and soil amendments on cation exchange capacity in 2013 and 2014 cropping seasons

Treatments	Cation exchange capacity ($cmol_c$ kg^{-1})	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	5.53	5.11
Tied ridge	5.52	5.86
Zai	6.12	6.20
Fpr	0.73	0.28
Lsd (0.05)	ns	ns
Organic manure (B) (kg ha^{-1})		
M0	5.24	5.16
M 2500	6.22	6.29
Fpr	0.01	< 0.001
Lsd (0.05)	0.74	0.55
Mineral fertilizer (C) (kg ha^{-1})		
0 N: 0 P_2O_5	5.05	4.92
20.5 N: 23 P_2O_5	5.90	6.19
41 N: 46 P_2O_5	6.62	6.07
Fpr	0.04	0.02
Lsd (0.05)	0.90	0.68
Int A x B	ns	ns
Int A x C	0.009	ns
Int B x C	ns	0.003
Int A x B x C	ns	ns
CV (%)	23.20	17.40

Int: Interaction, ns: not significant at F probability 5 %

Table 4.30: Interactive effect of organic manure and mineral fertilizer on cation exchange capacity in 2014 cropping season

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Cation exchange capacity (cmol$_c$ kg^{-1})
M0	0 N: 0 P_2O_5	3.66
	20.5 N: 23 P_2O_5	5.82
	41 N: 46 P_2O_5	5.99
M 2500	0 N: 0 P_2O_5	6.18
	20.5 N: 23 P_2O_5	6.55
	41 N: 46 P_2O_5	6.15
	Fpr	0.012
	Lsd (0.05)	0.95

4.5.2 Discussion

4.5.2.1 Effects of water harvesting techniques and soil amendments on soil pH

Soil pH plays a key role in enhancing plant nutrients availability (Rahman and Ranamukhaarachchi, 2003). It affects the activities of soil microorganisms and ultimately influences both organic matter decomposition and nutrient accessibility. In the current study, zai and tied ridge significantly ($P < 0.05$) increased soil pH. This could be due to the higher soil moisture content in the water harvesting techniques which increased soil microbial activities that consequently increased the decomposition of organic manure applied in these water harvesting structures. According to Magdoff and Weil (2004), application of manure to the soil is an effective strategy for reducing aluminum saturation in subsoil horizon. Furthermore, Mugwe *et al.* (2009b) indicated that cattle manure proved to be the most effective and improved soil fertility by increasing pH. In the present study mineral fertilizer did not affect soil pH. The results corroborate with the work of Bekunda *et al.* (1997) who found that continuous

application of inorganic input (especially N fertilizer) exclusive of organic fertilizer led to soil acidification and decline in soil organic matter. Interactive effect of water harvesting techniques and mineral fertilizer influenced soil pH in 2014. It is also observed that soil pH was influenced by interaction between manure and mineral fertilizer in 2014 cropping season.

4.5.2.2 Effects of water harvesting techniques and soil amendments on soil available phosphorus

There was a significant change in soil available P during the two cropping seasons as a result of management options applied. The change in available P could be explained by the solubility of rock phosphate and manure decomposition under zai and tied ridge.

This result is in close agreement with the previous result reported by Nnadi and Haque (1988) that direct application of rock phosphate was beneficial to crops on acid soils and could increase soil available P up to 115 %. The observation that available P contents of the soil were higher in 2014 than 2013 could be explained by the gradual release of nutrients from the decomposition of manure and the solubilization of the rock phosphate (RP). In a study conducted in Ghana, Danso *et al.* (2010) reported that available phosphorus level increased gradually after rock phosphate application. The increase in P availability in the current study may also be attributed to the conversion of rock phosphate

P to water-soluble form by the organic acids from the decomposition of manure (Khanna *et al.*, 1983).

4.5.2.3 Effects of water harvesting techniques and soil amendments on soil total nitrogen

The low nitrogen content could be particularly due to the low soil organic carbon levels (0.29 – 0.45 %) found in this study following water harvesting techniques and soil amendments. Similarly, Kiba (2012) showed low levels of total nitrogen under cropping system in Burkina Faso. The highest level of soil total nitrogen observed under manure and or mineral fertilizer treatments in 2014 were due to the organic matter content improvement under these plots. According to Kemmitt *et al.* (2008), soil organic matter is composed of 5 - 6 % nitrogen. The result from interaction of zai with manure and mineral fertilizer showed a higher nitrogen content that could be explained by the fact that the urea and the manure were applied in the seed hole. This provided more nitrogen due to closer proximity between the amendments and roots. Similar result was reported by Efthimiadou *et al.* (2010) who found that combined use of NPK and farmyard manure increased SOM, total N, Olsen P and ammonium acetate exchangeable K by 47, 31, 13 and 73 % respectively compared to the application of NPK through inorganic fertilizer.

4.5.2.4 Effects of water harvesting techniques and soil amendments on soil organic carbon

Low soil organic carbon content was observed under water harvesting techniques and nutrient management options. This could be due to rapid decomposition of manure in the soil. The best productive soils have 2.3 % of organic carbon and above (Metson, 1961).

In this study, water harvesting techniques did not affect soil organic content in 2013 while it did in 2014. This could be explained by the increased availability of organic matter and soil moisture. Manure decomposition through mineralization released organic carbon, macro and micronutrients in the soil. This observation was in line with results of Lashermes *et al.* (2009) which indicated that the addition of exogenous organic matter, like compost resulted in an enhancement of soil organic carbon storage and improved many functions of the soil related to the presence of organic matter. The impact of cattle manure application on soil organic carbon stock changes is of interest for both agronomic and environmental purposes. Maillard and Angers (2014) quantified the response of soil organic carbon stocks to manure application from a large pool of individual studies and reported a dominant effect of cumulative manure input on SOC response which accounted for at least 53 % of the variability in SOC stock. Mineral fertilizer did not influence soil organic carbon content in 2013. This observation is in close agreement with the study reported by Bationo *et al.* (2007) who showed that sole application of mineral fertilizer enhanced crop yields but did not sustain soil organic carbon.

4.5.2.5 Effects of water harvesting techniques and soil amendments on soil exchangeable potassium

Amount of soil exchangeable potassium decreased from the first to the second cropping season. In compost, soil exchangeable K remains in water-soluble forms and thus does not need to be mineralized before becoming plant available. However, for the same reason it is at risk of leaching during the composting process and thus compost is often a poor source of soil exchangeable K (Barker, 1997). Composting of organic wastes does not appear to affect exchangeable K availability but application of both compost and mineral potassium may affect soil exchangeable K (Baziramakenga *et al.*, 2001; Wen *et al.*, 1996). The exchangeable potassium decreased from 2013 to 2014 that could be explained by the crop high K uptake or leaching of K in the soil. In a related study, Adeleye *et al.* (2010) showed that addition of mineral fertilizer to poultry manure increased soil nutrients (organic carbon, N, P, K) more than the application of NPK or poultry manure alone even one year after their application.

4.5.2.6 Effects of water harvesting techniques and soil amendments on cation exchange capacity

The manure application significantly increased soil CEC that could be attributed to the anions (NO^{3-} and OH^{-}), the macronutrient (Ca, Mg and K) and the micronutrient (Fe, Cu, Mn and Zn) added to the soil through manure decomposition. Kincaid (2002) indicated that the cation exchange capacity of soils is largely related to the soil organic matter content. Organic matter can be added to soil by applying green manure, compost or animal manure (McDonagh *et al.*, 2001). Manure applied at a rate that supplied 30 kg ha^{-1} led to a significant increase in CEC, exchangeable bases (Ca, Mg and K), and base saturation (Zingore *et al*., 2008). Farmers (in Mali) often rotate sorghum and millet or occasionally maize with cotton to take advantage of the residual fertilizer effects by improved the CEC (Kablan *et al*., 2008).

The increased of CEC after rock phosphate and urea could be explained by the fact that the solubilization of Tilemsi rock phosphate improved soil calcium content and enchanced the CEC. The higher CEC recorded under zai than conventional tillage could be due to (i) decomposition of available crop residue and (ii) the faster rock phosphate dissolution as a result of higher moisture storage under zai.

4.6 Assessment of water harvesting techniques and soil amendments application on N and P use efficiencies and partial N and P balances

4.6.1 Results

4.6.1.1 Effect of water harvesting techniques and soil amendments on pearl millet N and P uptake

Tables 4.31 and 4.33 indicate the effects of water harvesting techniques and nutrient management options on pearl millet grain and straw N and P uptake.

In 2013 water harvesting techniques did not affect grain nitrogen uptake but influenced grain phosphorus uptake. A higher (10.96 kg ha^{-1}) nitrogen uptake was recorded under zai and a lower value (8.70 kg ha^{-1}) was observed under conventional tillage. Phosphorus uptake under tied ridge was about 42 % higher than under conventional tillage. Soil amendment management options significantly ($P < 0.05$) affected grain N and P uptake.

Nitrogen and phosphorus uptake under manure treatments were 38.47 and 37.00 %, respectively higher than the control. The mineral fertilizer treatment 41 kg N: 46 kg P_2O_5 ha^{-1} recorded a higher value of N (11.76 kg ha^{-1}) and P (6.61 kg ha^{-1}) uptake than the control N (7.31 kg ha^{-1}) and P (4.07 kg ha^{-1}). In 2013 cropping season, the pearl millet straw N uptake was affected by water harvesting techniques whilst straw P uptake did not increased. Zai improved N uptake by 16.61 %. The straw N and P uptake were significantly different ($P < 0.05$) under soil amendments. The manure treatment increased straw N uptake by 13.46 %, while the high level of mineral fertilizer increased the N uptake by 49.05 % as compared to the control.

Interactive effect of manure and mineral fertilizer applications increased grain N and P uptake (Tables 4.32). Combined application of manure at 2500 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} recorded a higher grain N and P uptake. Straw N uptake was influenced by interaction between water harvesting techniques and manure application (Appendix 14). The combined use of zai with manure at 2500 kg ha^{-1} gave the highest straw N uptake. The interaction between water harvesting techniques and mineral fertilizer application impacted on straw N uptake (Appendix 16). The combined use of conventional tillage with mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} recorded the highest straw N uptake. The interactive effect of water harvesting techniques, manure and mineral fertilizer applications significantly affected straw N uptake (Table 4.34). Combined use of conventional tillage with manure at 0 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} gave the highest straw N uptake.

In 2014 water harvesting techniques significantly ($P < 0.05$) affected pearl millet grain N and P uptake. A higher N uptake (19.38 kg ha^{-1}) was obtained under zai and a lower value (12.65 kg ha^{-1}) of N uptake was reported under conventional tillage. A higher value (12.32 kg ha^{-1}) of P uptake was reported under zai and a lower value (7.20 kg ha^{-1}) P uptake under conventional tillage. Nitrogen uptake was 52.75 % higher under zai as compared to N uptake under conventional tillage. The phosphorus uptake was 71 and 57 % under zai pit and tied ridge, respectively as compared to phosphorus uptake under conventional tillage. Soil amendments significantly ($P < 0.05$) affected grain N and P uptake. The mineral fertilizer application significantly ($P < 0.001$ and $P = 0.01$) influenced N and P uptake as compared to the control. In the 2014 cropping season, straw N uptake was influenced by water harvesting techniques, while P uptake was not (Table 4.33). The N and P uptake were significantly different ($P < 0.05$) under soil amendments. The manure application increased nitrogen straw uptake by 36.29 % while it improved phosphorus uptake by 44.41 % over the control. The mineral fertilizer application increased straw N uptake by 30.95 % under 20.5 kg N: 23 kg P_2O_5 ha^{-1} treatment and the straw P uptake by 46.76 % under 41 kg N: 46 kg P_2O_5 ha^{-1} treatment as compared to the control.

The interactive effects of manure and mineral fertilizer applications significantly ($P < 0.05$) influenced grain N and P uptake (Table 4.32). Combined application of manure at 2500 kg ha^{-1} and mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} recorded the highest grain N and P uptake. Interactive effects of water harvesting techniques and mineral fertilizer application significantly ($P < 0.05$) enhanced grain N uptake (Appendix 14). The highest grain N uptake was recorded under the use of zai with mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1}, while the lowest was obtained under the use of conventional tillage without mineral fertilizer application. The combined use of water harvesting techniques, manure and mineral fertilizer applicatios significantly ($P < 0.05$) increased straw P uptake (Table 4.34). Combined use of tied ridge with manure at 2500 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} gave the highest P uptake.

Table 4.3

1: Effects of water harvesting techniques on pearl millet grain N and P uptake in 2013 and 2014 cropping seasons

Treatments	Uptake (kg ha^{-1})			
	2013		2014	
	N Grain	P Grain	N Grain	P Grain
Water harvesting techniques (A)				
Conventional tillage	8.70	4.41	12.65	7.20
Tied ridge	10.28	6.27	15.94	11.29
Zai	10.96	6.06	19.38	12.32
Fpr	0.290	0.021	0.011	0.002
Lsd (0.05)	ns	1.16	3.23	3.50
Organic manure (B) (kg ha^{-1})				
M0	8.37	4.71	12.30	8.55
M 2500	11.59	6.45	19.68	11.20
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	1.10	0.65	2.08	2.50
Mineral fertilizer (C) (kg ha^{-1})				
0 N: 0 P_2O_5	7.31	4.07	12.32	9.16
20.5 N: 23 P_2O_5	10.88	6.07	20.62	11.20
41 N: 46 P_2O_5	11.76	6.61	15.03	10.46
Fpr	< 0.001	< 0.001	< 0.001	0.010
Lsd (0.05)	1.34	0.79	2.54	3.06
Int A x B	ns	ns	ns	ns
Int A x C	ns	ns	< 0.001	ns
Int B x C	0.003	< 0.001	0.030	0.04
Int Ax B x C	ns	ns	ns	ns
CV (%)	19.80	21.00	23.40	19.10

Table 4.3
Int: Interaction, ns: not significant at F probability 5 %

2: Interactive effect of manure and mineral fertilizer on pearl millet grain N and P uptake in 2013 and 2014 cropping seasons

Manure ($kg\ ha^{-1}$)	Mineral fertilizer ($kg\ ha^{-1}$)	Grain N and P uptake ($kg\ ha^{-1}$)			
		2013		2014	
		N	P	N	P
M0	0 N: 0 P_2O_5	4.64	2.26	7.10	6.58
	20.5 N: 23 P_2O_5	10.65	6.10	16.50	9.69
	41 N: 46 P_2O_5	9.82	5.77	13.30	9.38
M 2500	0 N: 0 P_2O_5	9.98	5.87	17.54	11.74
	20.5 N: 23 P_2O_5	11.10	6.04	24.75	12.70
	41 N: 46 P_2O_5	13.69	7.45	16.75	11.54
	Fpr	0.003	< 0.001	0.030	0.040
	Lsd (0.05)	1.90	1.13	3.60	1.89

Table 4.3

3: Effects of water harvesting techniques and soil amendments on pearl millet straw N and P uptake in 2013 and 2014 cropping seasons

Treatments	Uptake (kg ha^{-1})			
	2013		2014	
	N straw	P straw	N straw	P straw
Water harvesting techniques (A)				
Conventional tillage	32.81	6.04	15.74	7.14
Tied ridge	28.36	7.74	12.08	7.49
Zai	38.26	9.03	13.30	7.33
Fpr	0.008	0.28	0.020	0.730
Lsd (0.05)	4.36	ns	2.05	ns
Organic manure (B) (kg ha^{-1})				
M0	31.05	6.85	11.60	5.99
M 2500	35.23	8.36	15.81	8.65
Fpr	0.005	0.030	0.002	< 0.001
Lsd (0.05)	2.82	1.25	2.56	1.08
Mineral fertilizer (C) (kg ha^{-1})				
0 N: 0 P_2O_5	28.01	5.82	11.76	5.88
20.5 N: 23 P_2O_5	29.67	8.26	15.40	7.45
41 N: 46 P_2O_5	41.75	8.72	13.95	8.63
Fpr	< 0.001	0.02	0.070	< 0.001
Lsd (0.05)	3.46	2.17	ns	1.33
Int A x B	0.003	ns	ns	ns

Table 4.3

Int A x C	< 0.001	ns	ns	ns
Int B x C	ns	ns	ns	ns
Int A x B x C	< 0.001	ns	ns	0.0340
CV (%)	15.30	42.10	33.70	26.70

Int: interaction, ns: not significant at F probability 5 %

Table 4.34: Interactive effects of water harvesting techniques, manure and mineral fertilizer on pearl millet straw N and P uptake in 2013 and 2014 cropping seasons

Water harvesting techniques	Manure (kg ha$_{-1}$)	Mineral fertilizer (kg ha$_{-1}$)	Straw N and P uptake (kg ha^{-1})	
			2013	2014
			N	P
C. tillage	M0	0 N: 0 P_2O_5	13.30	3.43
		20.5 N: 23 P_2O_5	31.37	7.92
		41 N: 46 P_2O_5	55.83	7.57
	M 2500	0 N: 0 P_2O_5	29.20	6.44
		20.5 N: 23 P_2O_5	30.32	9.13
		41 N: 46 P_2O_5	36.85	8.37
Tied ridge	M0	0 N: 0 P_2O_5	15.31	5.41
		20.5 N: 23 P_2O_5	27.02	6.78
		41 N: 46 P_2O_5	38.53	6.13
	M 2500	0 N: 0 P_2O_5	34.75	7.00
		20.5 N: 23 P_2O_5	22.60	8.19
		41 N: 46 P_2O_5	31.93	11.41
Zai	M0	0 N: 0 P_2O_5	33.02	2.47
		20.5 N: 23 P_2O_5	29.61	5.63
		41 N: 46 P_2O_5	35.47	8.57
	M 2500	0 N: 0 P_2O_5	42.49	10.54
		20.5 N: 23 P_2O_5	37.09	7.03
		41 N: 46 P_2O_5	51.87	9.71
		Fpr	< 0.001	0.034
		Lsd (0.05)	8.33	26.70

C. tillage: Conventional tillage

4.6.1.2 Nitrogen and phosphorus utilization efficiencies under different water harvesting techniques and soil amendment management options

Water harvesting techniques significantly ($P = 0.003$ in 2013 and $P = 0.02$ in 2014) affected nitrogen utilization efficiency but did not influence phosphorus utilization efficiency (Table 4.35). The nitrogen utilization efficiencies obtained were 58.5 kg kg^{-1} under tied ridge followed by 54.0 kg kg^{-1} under zai pit and 38.2 kg kg^{-1} under conventional tillage. Phosphorus utilization efficiency under tied ridge and zai showed an average of 26.6 and 18.4 % increases, respectively over the conventional tillage in 2014.

In both 2013 and 2014, neither manure nor mineral fertilizer application significantly affected the magnitude of N and P utilization effeciencies.

Table 4.35: Effects of water harvesting techniques and soil amendments on pearl millet (straw and grain) N and P utilization efficiency in 2013 and 2014 cropping seasons

Treatments	Nutrient use efficiency (kg kg^{-1})			
	2013		2014	
	NUE	PUE	NUE	PUE
Water harvesting techniques (A)				
Conventional tillage	38.20	85.20	20.18	72.20
Tied ridge	58.50	77.20	29.13	85.50
Zai	54.00	78.10	26.21	91.40
Fpr	0.003	0.55	0.020	0.07
Lsd (0.05)	7.30	ns	5.07	ns
Organic manure (B) (kg ha^{-1})				
M0	46.90	79.3	25.93	85.60
M 2500	53.60	81.00	24.42	80.50
Fpr	0.070	0.8	0.420	0.24
Lsd (0.05)	ns	ns	ns	ns
Mineral fertilizer (C) (kg ha^{-1})				
0 N: 0 P_2O_5	46.00	84.40	25.45	80.20
20.5 N: 23 P_2O_5	51.70	78.7	26.02	84.44
41 N: 46 P_2O_5	53.10	77.3	24.06	84.50
Fpr	0.22	0.65	0.68	0.65
Lsd (0.05)	ns	ns	ns	ns
Int A x B	ns	ns	ns	ns
Int A x C	ns	ns	ns	ns
Int B x C	ns	ns	ns	ns
Int A x B x C	ns	ns	ns	ns
CV (%)	25.30	30.00	27.30	18.90

Int: interaction, ns: not significant at F probability 5 %

4.6.1.3 Assessment of the effect of water harvesting techniques and soil amendments application on partial N and P balances

Water harvesting techniques affected partial nutrient balance significantly ($P < 0.05$) (Table 4.36). In 2014 the highest partial N and P balances were recorded under conventional tillage, whilst the lowest value was obtained under zai pit technique. The manure application significantly ($P < 0.001$) influenced partial P and N balances. In both 2013 and 2014, the partial balance was positive for P and N under manure application, while that of the control was negative. The application of mineral fertilizer significantly ($P < 0.001$) influenced partial N and P balances. The balance was negative under the control and positive under different rates of mineral fertilizer. The recommended rate of mineral fertilizer had the highest value of partial N and P balances.

Interactive effects of water harvesting techniques, manure and mineral fertilizer significantly ($P < 0.05$) influenced the partial N balance (Table 4.37). Combined use of conventional tillage with manure at 2500 kg ha^{-1} and mineral fertilizer at 41 kg N: 46 kg P_2O_5 ha^{-1} gave the highest partial N balance. Interactive effect of water harvesting techniques and manure application significantly ($P < 0.05$) affected partial N balance (Appendix 17). The combined use of conventional tillage with manure at 2500 kg ha^{-1} gave the highest partial N balance, while the lowest value was obtained with the use of tied ridge without manure application. The combined application of manure and mineral fertilizer significantly ($P < 0.05$) influenced partial N balance (Appendix 18). Combined application of manure at 2500 kg ha^{-1} and mineral fertilizer at 46 kg N: 46 kg P_2O_5 ha^{-1} gave the highest partial N balance, while the lowest was obtained on plots with neither manure nor mineral fertilizer application.

Table 4.36: Effects of water harvesting techniques and soil amendments on partial nutrient balance in 2013 and 2014 cropping seasons

Treatments	Partial nutrient balance (kg ha^{-1})			
	2013		2014	
	N	P	N	P
Water harvesting techniques (A)				
Conventional tillage	-1.30	10.22	11.98	6.43
Tied ridge	0.90	6.87	1.36	1.99
Zai	-10.10	4.29	1.37	1.12
Fpr	0.020	0.04	0.040	0.002
Lsd (0.05)	3.80	4.21	8.49	1.76
Organic manure (B) (kg ha^{-1})				
M0	-18.90	-2.13	-17.30	-4.51
M 2500	11.90	16.39	27.10	10.86
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	4.45	1.91	3.85	1.77
Mineral fertilizer (C)) (kg ha^{-1})				
0 N: 0 P_2O_5	-16.70	-0.56	-13.26	-4.30
20.5 N: 23 P_2O_5	-1.00	6.72	5.21	2.12
41 N: 46 P_2O_5	7.20	15.23	22.75	11.70
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	5.45	2.34	4.72	2.16.
Int A x B	0.049	ns	0.012	ns
Int A x C	ns	ns	ns	ns
Int B x C	< 0.001	ns	ns	ns
Int A x B x C	0.009	ns	ns	ns
CV (%)	229.10	48.3	141.30	100.1

Int: Interaction, ns: not significant at F probability 5 %

Table 4.37: Interactive effect of water harvesting techniques and soil amendments on partial N balance at 0 – 20 cm depth in 2013 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Partial N balance (kg ha^{-1})
C. tillage	M0	0 N: 0 P_2O_5	-16.90
		20.5 N: 23 P_2O_5	-20.10
		41 N: 46 P_2O_5	-22.40
	M 2500	0 N: 0 P_2O_5	-1.40
		20.5 N: 23 P_2O_5	16.80
		41 N: 46 P_2O_5	36.30
Tied ridge	M0	0 N: 0 P_2O_5	-20.50
		20.5 N: 23 P_2O_5	-16.90
		41 N: 46 P_2O_5	-8.10
	M 2500	0 N: 0 P_2O_5	-7.30
		20.5 N: 23 P_2O_5	25.80
		41 N: 46 P_2O_5	32.30
Zai	M0	0 N: 0 P_2O_5	-38.20
		20.5 N: 23 P_2O_5	-21.40
		41 N: 46 P_2O_5	-5.80
	M 2500	0 N: 0 P_2O_5	-16.00
		20.5 N: 23 P_2O_5	9.70
		41 N: 46 P_2O_5	11.20
		Fpr	0.009
		Lsd (0.05)	12.47

C. tillage: Conventional tillage

4.6.2 Discussion

4.6.2.1 Effect of water harvesting techniques and soil amendments on pearl millet N and P uptake

Nitrogen uptake by pearl millet grain and straw was significantly higher under zai pit and tied ridge techniques than the conventional tillage due to availability of soil moisture and better root growth that favoured nutrient uptake. Fatondji (2002) found that zai improved nitrogen uptake in the range of 43 - 64 %. Barker and Pilbeam (2007) indicated that nutrient uptake is influenced mainly by climatic conditions, the quantity of available nutrients in the soil and the form in which they are present in the soil. Nitrogen uptake by pearl millet grain and straw was significantly higher under manure or mineral fertilizer application due to the fact that manure conserved moisture and released slowly nutrient in the soil. The mineral nitrogen was available for rapid plant use which facilitated root development, early growth of crop and increased nitrogen uptake.

The increased straw N uptake (36.29% due to the application of M 2500 kg ha^{-1} of manure corroborate with the result of similar study reported by Ballaki and Badanur (2012) who indicated increase in N uptake by sorghum with addition of organic fertilizer over the control. The findings obtained from the combined use of cattle manure and mineral fertilizer also support those of Nyamangara *et al.* (2013),.

Phosphorus uptake was higher under zai (71 %) and tied ridge (57 %) than the conventional tillage. The increase in P uptake under water harvesting techniques could be explained by the enhancement of soil moisture content which led to crop growth. Ouattara (1994) reported a positive interaction between soil moisture and P uptake due to improved soil moisture status increased soil P availability. The greater phosphorus uptake values in grain of pearl millet were recorded under M 2500 kg ha^{-1} and 20.5 kg N: 23 kg P_2O_5 ha^{-1} treatment. However, higher straw P uptakes values were observed in the M 2500 kg ha^{-1} and 41 kg N: 46 kg P_2O_5 ha^{-1} treatments. This may be attributed to increased absorption of P by plants due to better root growth with additional nitrogen supply through manure. Hellal *et al.* (2013) reported that phosphorus enriched with farmyard manure was most effective in increasing phosphorus availability and uptake in soil as well as increasing dry matter yield of maize.

4.6.2.2 Nitrogen and phosphorus utilization efficiencies under different water harvesting techniques and soil amendment management options

Nitrogen use efficiency was significantly ($P < 0.05$) higher under zai and tied ridge than to that of the conventional tillage. This could be due to water availability, root proliferation which enhanced greater utilization of soil moisture, improved nutrient uptake and increased grain yield of the pearl millet. Similarly, Fatondji (2002) reported a high N concentration in pearl millet grain under zai compared to flat planting. Rehman *et al.* (2011) showed that nitrogen use efficiency was highest with ridge planting, and reported that this soil manipulation could have resulted in lower N losses (leaching), while plant roots grew abundantly to take up nutrients from a richer soil solution. Combined application of mineral fertilizers and manure had no significant influence on pearl millet nitrogen use efficiency. Moreover, the application of manure did not increased phosphorus use efficiency of pearl millet. Contrary results was reported by Fatondji (2002), organic amendment application increased grain phosphorus utilization efficiency by 2 times compared to the control treatment.

4.6.2.3 Assessment of the effect of water harvesting techniques and soil amendments on partial N and P balances

Water harvesting techniques affected partial N and P balances significantly ($P < 0.05$). The partial N and P balances were positive under the three practices. The highest values of partial phosphorus (10.22 kg ha^{-1}) in 2013 and nitrogen (11.98 kg ha^{-1}) in 2014 balances were recorded under conventional tillage, while the lowest value was obtained under zai. This could be explained by the fact that zai and tied ridge conserved moisture better and made nutrients available in soil solution. The grain and straw yield produced under these harvesting techniques were higher and therefore N and P export from the soil has higher than the conventional tillage. Ramisch (1999) reported that a large addition of nutrients (and indeed of labour and management energy) can often stimulate an improved biomass production from the plot, but this in turn extracts considerable quantities of nutrients from the soil.

Manure applied at 2500 kg ha^{-1} gave positive partial N and P balances that could be attributed to soil management practices, while partial N and P balances were negative under control. The positive balances in N and P were recorded where the recommended rate of mineral fertilizer (20.5 kg N: 23 P_2O_5 ha^{-1} and 41 kg N: 46 P_2O_5 ha^{-1}) was applied, while the balances remained negative in control plots. This result indicates that the application of recommended amount mineral fertilizer seems to be adequate in maintaining N and P balances. The results contrasted with the negative N and P balances reported by FAO (2005) for pearl millet production in Mali.

4.7 Economic analysis

4.7.1 Results

4.7.1.1 Partial factor of productivity of pearl millet

The results of the water harvesting techniques and soil amendments on partial factor of productivity are presented in Table 4.38. Partial factor of productivity under pearl millet was significantly ($p < 0.05$) influenced by water harvesting techniques. At the end of the study the highest N partial factor of productivity value was recorded by zai (47.43 kg grain kg^{-1} N), while the lowest was obtained by conventional tillage (28.62 kg grain kg^{-1} N). Zai recorded the highest phosphorus partial factor of productivity (39.64 kg grain kg^{-1} P) and the lowest was obtained by conventional tillage (24.07 kg grain kg^{-1} P).

Soil amendments significantly ($p < 0.001$) affected partial factor of productivity. The highest value of N partial factor of productivity was recorded by treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} (68.27 kg grain kg^{-1} N), while the lowest was obtained by treatment 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} (22.07 kg grain kg^{-1} N). The trend of N partial factor of productivity was 20.5 kg N: 23 kg P_2O_5 ha^{-1} > M 2500 kg ha^{-1} > 41 kg N: 46 kg P ha^{-1} > 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} > 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1}. The phosphorus partial factor of productivity followed the same trend where the treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} recorded 60.85 kg grain kg^{-1} P and the poor treatment had (18.02 kg grain kg^{-1} P).

Table 4.38: Effects of water harvesting techniques and soil amendments management options on partial factor of productivity in 2013 and 2014 cropping seasons

Treatment	Partial factor of productivity (kg grain kg^{-1})			
	2013		2014	
	NPFP	PPFP	NPFP	PPFP
Water harvesting techniques (A)				
Conventional tillage	22.21	18.57	28.62	24.07
Tied ridge	28.49	23.82	42.96	35.97
Zai	32.05	26.79	47.43	39.64
Fpr	0.03	0.03	0.001	0.002
Lsd (0.05)	6.07	5.45	5.39	4.62
Soil amendment (AM)) (kg ha^{-1})				
0 N: 0 P_2O_5	-	-	-	-
20.5 N: 23 P_2O_5	50.95	45.41	68.27	60.85
41 N: 46 P_2O_5	22.94	20.45	36.33	32.39
M 2500	27.29	20.64	41.50	30.96
20.5 N: 23 P_2O_5 + M 2500	19.25	14.82	30.18	23.91
41 N: 46 P_2O_5 + M 2500	17.51	13.98	22.07	18.02
Fpr	< 0.001	< 0.001	< 0.001	< 0.001
Lsd (0.05)	6.21	5.42	6.51	5.54
Int A x AM	ns	ns	ns	ns
CV (%)	23.10	24.20	16.90	17.10

Int: Interaction, ns: not significant at F probability 5 %

4.7.1.2 Value cost ratio of the pearl millet production

The returns on investments in manure and mineral fertilizer applications were appraised by the value cost ratio (VCR) estimates. In both cropping seasons, water harvesting techniques significantly affected the VCR. The highest value 2.66 - 3.27 was recorded by zai pit technique and the lowest value 1.64 – 1.92 was obtained by the conventional tillage (Figure 4.3).

All treatments had value cost ratio higher than 1 (Figures 4.4). However, the application of low rates of manure resulted in higher value cost ratios M 2500 kg ha^{-1} (3.15 - 3.67) followed by low ratios of mineral fertilizer treatment 20.5 kg N: 23 kg P_2O_5 ha^{-1} (2.94 - 3.25). The application of combined manure and mineral fertilizer 41 kg N: 46 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} had the lowest VCR values 1.55 – 1.67.

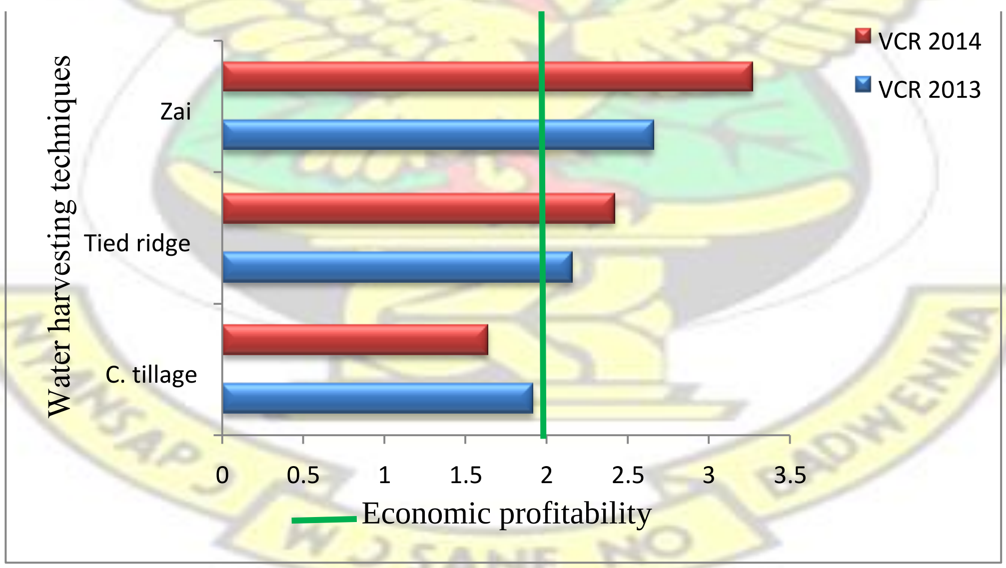


Figure 4.3: Effects of water harvesting techniques on value cost ratio in 2013 and 2014 cropping seasons

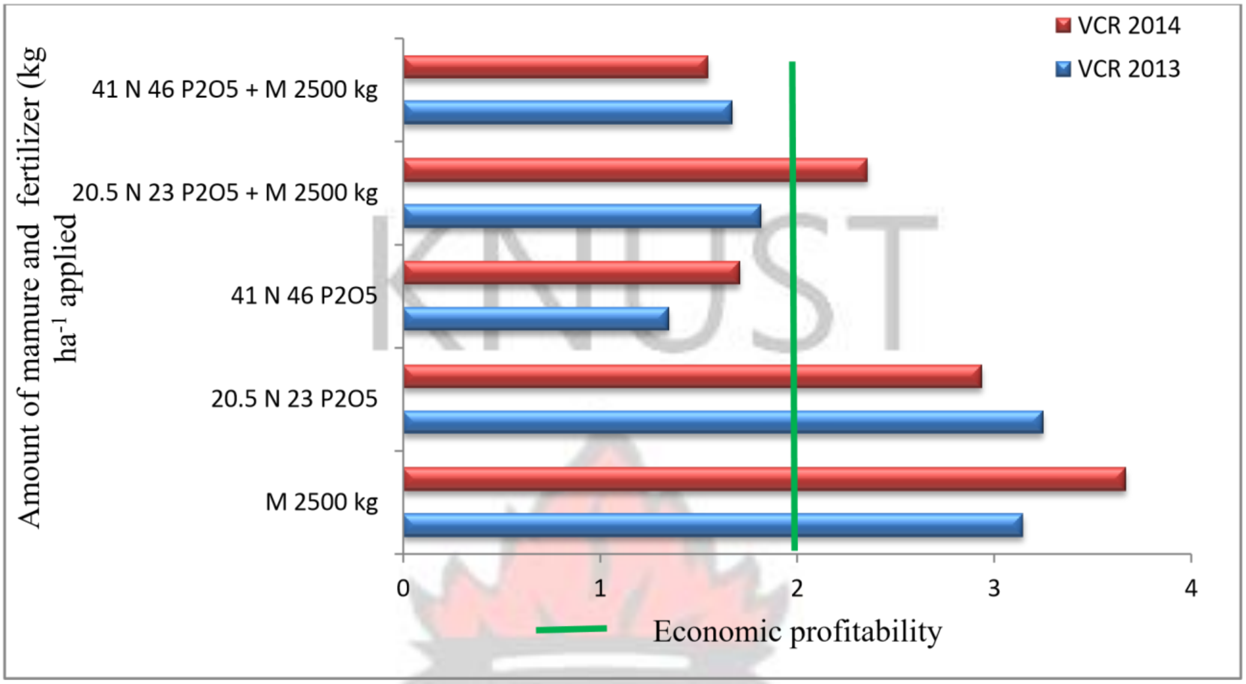


Figure 4.4: Effect of manure and mineral fertilizer on value cost ratio in 2013 and 2014 cropping seasons

4.7.1.3 Net farm benefit from water harvesting techniques and soil amendments

Table 4.39 presents the net farm benefit (NFB) for pearl millet production using water harvesting techniques and soil amendments. Water harvesting techniques significantly ($p < 0.05$) increased the net farm benefit.Tied ridge had produced significantly higher benefit (80214 FCFA ha^{-1}), than under conventional tillage (48349 FCFA ha^{-1}) in 2013 cropping season. The trend of the NFB was tied ridge > zai > conventional tillage. The highest benefit obtained by tied ridge (171780 FCFA ha^{-1}) was significantly greater than under conventional tillage (89780 FCFA ha^{-1}) in 2014 cropping season.

In 2013 the the highest net farm benefit was obtained by 41 kg N: 46 kg P_2O_5 ha^{-1} +

M 2500 kg ha^{-1} yielded 86034 FCFA ha^{-1}, while the least treatment (control) had 9220 FCFA ha^{-1}. In 2014 all the soil amendment treatments had net farm benefit superior to the control. The best soil amendment treatment was 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} with 169872 FCFA followed by the M 2500 kg ha^{-1} with 162242 FCFA ha^{-1} and the least treatment was 0 kg N: 0 kg P_2O_5 ha^{-1} treatment with 76592 FCFA ha^{-1}.

Table 4.39: Effects of water harvesting techniques and soil amendments on net farm benefit in 2013 and 2014 cropping seasons

Treatments	Net farm benefit (FCFA ha^{-1})	
	2013	2014
Water harvesting techniques (A)		
Conventional tillage	48349	89780
Tied ridge	80214	171780
Zai	55577	150095
Fpr	0.03	0.001
Lsd (0.05)	8017	7991
Soil amendment (AM) **)** (kg ha^{-1})		
0 N: 0 P_2O_5	9220	76592
20.5 N: 23 P_2O_5	83395	141364
41 N: 46 P_2O_5	41041	130672
M 2500	79282	162242
20.5 N: 23 P_2O_5 + M 2500	69309	169872
41 N: 46 P_2O_5 + M 2500	86034	142569
Fpr	< 0.001	0.002
Lsd (0.05)	2944.20	19040.60
Int A x AM	ns	ns

Int: interaction; 1 dollar: 585 FCFA, ns: not significant at F probability 5 %

4.7.2 Discussion

4.7.2.1 Partial factor of productivity of pearl millet

Pearl millet had higher partial factor productivity (PFP) of nitrogen and phosphorus under zai followed by tied ridge and conventional tillage. The PFP were higher in the second year (2014) than the first year (2013) as shown in the Table 4.38. This could be due to the rainfall variability between the two years. Similar results showed that maize nitrogen productivity varied greatly from year to year based on environmental conditions (Harold *et al.*, 2006). Okalebo *et al.* (2006) suggested that site specific recommendations are needed for maize because of its differential response to nutrient inputs which varied widely within and across agro-ecological zones. Wang *et al.* (2007) reported that understanding concepts of ideal soil fertility level and response to nutrient management provide practical guidelines for improving nutrient management under variable rainfall conditions.

The highest partial factor of productivity of N and P were obtained under manure application while the lowest PFP was reported under 41 kg N: 46 kg P_2O_5 ha^{-1} of mineral fertilizer combined with manure. The results obtained in the current study indicated that increasing rate of applied nutrients (N and P) lead to a decrease in partial factor of productivity. This could be explained by the fact that grain yield increased did not follow the rate of increasing fertilizer. This result supports the finding of Kareem and Ramasamy

(2000) that higher fertilizer use efficiency is always associated with low fertilizer application rate.

4.7.2.2 Value cost ratio of the pearl millet production

It is indicated that treatment is profitable when the value cost ratio is greater than 2. Heerink (2005) stated that technically, VCR greater than 2 would imply profitability of fertilizer as long as other inputs were not altered as the use of fertilizer. Among the soil amendments, the sole manure gave the best profitability as indicated by its VCR value in the range of 3.15 to 3.67 under pearl millet. This could be attributed to the increase in grain yield from the use of manure, which is less costly than mineral fertilizers in Mali (10 FCFA kg^{-1}). The VCRs under the low rate of mineral fertilizer and in combination with manure were greater than two as a result of the low cost of these treatments. Similarly, Mkhabela (2003) reported higher financial benefits from supplementing manure with mineral fertilizer relative to using sole manure. The high rate of mineral fertilizer and its combination with manure had lower value of VCR due to the high price of mineral fertilizer. Dembélé and Savadogo (1996) reported that the low profitability of inorganic fertilizer in West Africa could be attributed to poor crop response. Contrastingly, Opoku (2011) found that 100 % of NPK and 2.5 Mg ha^{-1} of manure increased the VCR to 7.6. This study has demonstrated that manure at 2500 kg ha^{-1} or the low mineral fertilizer rate treatment (20.5 kg N: 23 kg P_2O_5 ha^{-1}) would be an appropriate nutrient strategy for optimizing returns on nutrient inputs at a reasonable cost.

4.7.2.3 Net farm benefit from water harvesting techniques and soil amendments

The farming practices which are profitable in the short-run usually attract farmers' interest and are therefore more likely to be adopted. Tied ridge and zai pit recorded greater net farm benefit than conventional tillage. This could be due to the high grain yield produced under these techniques. In this study the best water harvesting techniques was tied ridge which resulted in high yield from low labour cost. It was followed by zai which produced more grain yield than the tied ridge but involved greater labour cost. These results are in agreement with the findings of Zougmoré *et al.* (2014) and Kaboré and Reij (2004) who reported that water harvesting techniques that produced greater grain yield, and low labour cost could increase the net benefit of farmers in Burkina Faso.

The application of manure and mineral fertilizer led to higher net farm benefit than the control. This could be explained by the higher grain yield of pearl millet grain yield and the low cost of manure. It could also be due to the higher market price of pearl millet grain. According to Abdoulaye and Sanders (2005) and Vitale and Sanders (2005), the price of cereals in the market play the key role in net benefit of farmers. The best profitable treatments were 20.5 kg N: 23 kg P_2O_5 ha^{-1} + M 2500 kg ha^{-1} followed by 41 kg N: 46 kg P_2O_5 + M 2500 kg ha^{-1}.

CHAPTER FIVE

5.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

The main objective of the current research was to increase grain yield of millet on smallholder farms, through the use of efficient nutrient management and water harvesting strategies.

i. Pearl millet height, grain and straw yields increased significantly under water harvesting techniques with the highest yields recorded under zai followed by tied ridge. Addition of soil amendments (mineral fertilizer and manure) to water harvesting techniques enhanced markedly pearl millet height, grain and straw yield. Zai recorded the highest yield followed by tied ridge and, then conventional tillage. Combined application of manure and mineral fertilizer increased pearl millet height, grain and straw yield. During the two cropping seasons, soil amendments application, but not zai and tied ridge, increased harvest index and agronomic efficiency.

ii. Soil moisture content was improved under zai techniques and tied ridge options and led to a significant increase in rainwater use efficiency. Soil amendment application increased rainwater use efficiency. In both years, interaction effect of manure and mineral fertilizer enhanced RWUE. The study has confirmed that water harvesting techniques caused significant variations in the bulk density and soil moisture storage. The capacity of zai and tied ridge at 0 - 20 cm depth to conserve water increased with increasing periods of moisture stress, making these water harvesting techniques better options for in-situ moisture storage under rainfed agriculture on smallholder farms for sustainable crop production. The combination of water harvesting techniques, manure and mineral fertilizer applications increased soil volumetric moisture content.

iii. Nutrients (N and P) uptake by pearl millet was higher under water harvesting techniques with the highest N and P uptake being recorded in the plots with zai treatments. The highest N and P utilization efficiencies were recorded in the plots that received the tied ridge and zai treatments, respectively. Manure and mineral fertilizer applications and their interactions enhanced grain and straw N and P uptake. Tied ridge, zai and conventional tillage produced positive partial N and P balances. Conventional tillage had the highest partial N and P balances while the lowest values were recorded under zai. Manure application at 2500 kg ha^{-1} had positive partial N and P balances but the control had negative partial N and P balances. Also, the application of half and recommended rates of N and P fertilizer had positive partial N and P balances.

iv. The value cost ratio and the partial factor of productivity were profitable for the use of M 2500 kg ha^{-1} and 20.5 kg N: 23 kg P_2O_5 ha^{-1}, respectively. The highest net benefit was obtained from the use of tied ridge and 20.5 kg N: 23 kg P_2O_5 ha^{-1} + 2500 kg ha^{-1} of manure and mineral fertilizer applications.

5.2 Conclusions

Based on the objectives and the results obtained in this study, the following conclusions were drawn:

i. Yields of pearl millet increased markedly with use of water harvesting techniques such as zai and tied ridge. These results suggest that the combined use of water harvesting techniques and soil amendments as an appropriate option for improved millet production in Mali.

ii. The use of soil amendments with either tied ridge or zai techniques increased soil moisture content and rainwater use efficiency. This result indicates that the application of zai and tied ridge technologies improves plant water availability for enhanced millet yields.

iii. Tied ridge or zai technique combined with soil amendments application resulted in a higher positive partial N and P balances. Application of 2500 kg ha^{-1} manure improved soil partial N and P balances. This implied that the recommended rate of mineral fertilizer leads to N and P accumulation. Nitrogen and phosphorus uptake were improved by the use of water harvesting techniques and soil amendments application. Moreover, water harvesting techniques improved N use efficiencies.

iv. Financial benefit was greater under zai and tied ridge. Manure and mineral fertilizer applications increased the value cost ratio, partial factor of productivity and net farm return. The tied ridge and zai combined with manure and mineral fertilizer applications could maintain the economic profitability of smallholder farmers.

5.3 Recommendations

i. Studies to evaluate the combined effect of water harvesting techniques and nutrient management options are warranted in the sudan and sudan – sahelian agroecological zones.

ii. The use of tied ridge and mineral fertilizer at 20.5 kg N: 23 kg P_2O_5 ha^{-1} with 2500 kg ha^{-1} of manure was most effective. Howerever, futher evaluation of this option is need to validate its performance.

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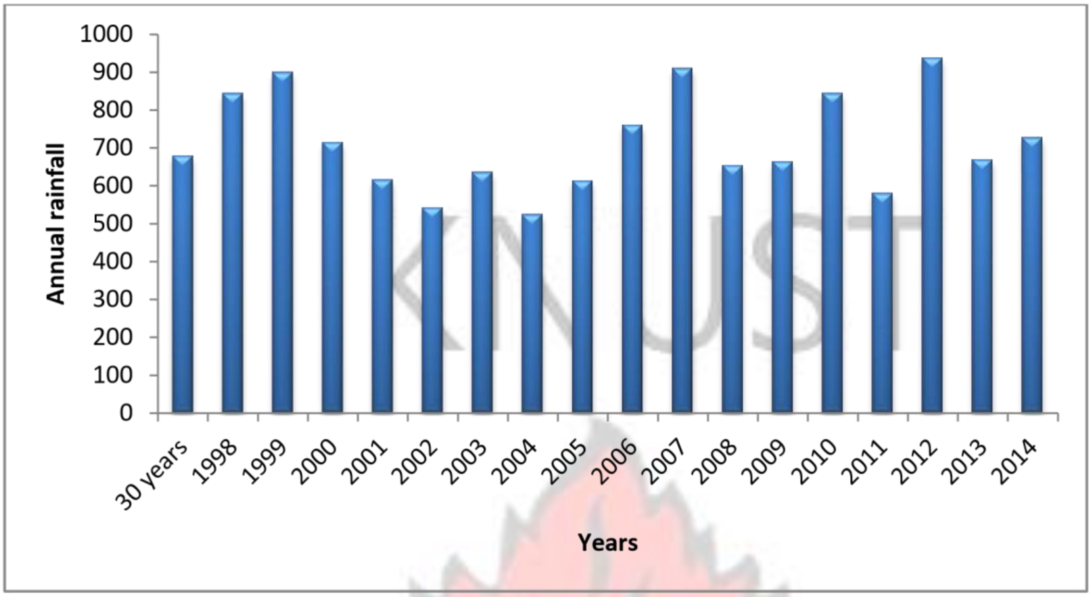
APPENDICES



Appendix 1: Mean annual rainfall of 30 years compared to the last seventeen years

Appendix 2: Interactive effect between water harvesting techniques and manure on plant height at maturity stage in 2013 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Plant height (cm) Maturity stage
C. tillage	M0	256.9
	M 2500	276.3
Tied ridge	M0	296.7
	M 2500	297.7
Zai	M0	289.6
	M 2500	318
	Fpr	0.005
	Lsd(0.05)	27.91

C. tillage: Conventional tillage

Appendix 3: Interactive effect of water harvesting techniques and manure on dry matter production at tillering and elongation stages in 2013 and 2014 cropping seasons

Water harvesting techniques	Manure (kg ha^{-1})	Dry matter production (g plant^{-1})	
		Tillering stage in 2013	Elongation stage in 2014
C. tillage	M0	1.24	52.40
	M 2500	1.28	51.10
Tied ridge	M0	1.40	37.00
	M 2500	1.37	55.60
Zai	M0	1.07	29.60
	M 2500	1.88	49.00
	Fpr	< 0.001	0.03
	Lsd (0.05)	0.29	16.76

C. tillage: Conventional tillage

Appendix 4: Interactive effect of water harvesting techniques and mineral fertilizer on dry matter production at tillering, elongation and 50 % flowering stages in 2013 and 2014 cropping seasons

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	Dry matter production (g plant^{-1})				
		2013		2014		
		Elongation stage	50 % flowering stage	Tillering stage	Elongation stage	50% flowering stage
C. tillage	0 N: 0 P_2O_5	15.30	86.50	1.79	38.90	146.50
	20.5 N: 23 P_2O_5	28.80	97.60	2.95	70.70	208.50
	41 N: 46 P_2O_5	26.50	99.70	1.57	45.60	250.20
Tied ridge	0 N: 0 P_2O_5	25.60	89.50	1.63	40.40	200.30
	20.5 N: 23 P_2O_5	33.50	123.80	190	41.10	206.60
	41 N: 46 P_2O_5	27.30	137.30	2.06	57.50	193.20
Zai	0 N: 0 P_2O_5	33.20	137.00	1.49	39.50	126.40
	20.5 N: 23 P_2O_5	31.20	113.00	1.62	35.60	130.40
	41 N: 46 P_2O_5	46.90	140.70	2.19	42.70	172.00
	Fpr	0.03	0.03	0.04	0.001	0.02
	Lsd (0.05)	11.30	28.08	1.02	18.04	73.64

C. tillage: Conventional tillage

Appendix 5: Interactive effect of manure and mineral fertilizer on dry matter production at elongation stage in 2014 cropping seasons

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Dry matter production (g plant^{-1})	
		Elongation stage	50 % flowering stage
M0	0 N: 0 P_2O_5	25.60	131.30
	20.5 N: 23 P_2O_5	42.40	191.60
	41 N: 46 P_2O_5	51.10	199.30
M 2500	0 N: 0 P_2O_5	53.60	184.20
	20.5 N: 23 P_2O_5	55.80	172.10
	41 N: 46 P_2O_5	46.10	211.00
	Fpr	0.001	0.03
	Lsd (0.05)	11.72	37.48

Appendix 6: Interactive effect of water harvesting techniques and manure application on soil bulk density 90 days after sowing at 20 – 40 cm depth in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Bulk density (g cm^{-3}) in 2014
		20 -40 cm
C. tillage	M0	1.55
	M 2500	1.50
Tied ridge	M0	1.49
	M 2500	1.41
Zai	M0	1.44
	M 2500	1.26
	Fpr	0.028
	Lsd (0.05)	0.11

C. tillage: Conventional tillage

Appendix 7: Interactive effect of water harvesting techniques and organic manure on available phosphorus in 2014 cropping season

Water harvesting techniques	Manure ($kg\ ha^{-1}$)	Available phosphorus ($mg\ kg^{-1}$)
C. tillage	M0	7.05
	M 2500	11.93
Tied ridge	M0	10.33
	M 2500	10.51
Zai	M0	8.13
	M 2500	19.69
	Fpr	< 0.001
	Lsd (0.05)	1.90

C. tillage: Conventional tillage

Appendix 8: Interactive effect of manure and mineral fertilizer on available phosphorus in 2014 cropping season

Manure ($kg\ ha^{-1}$)	Mineral fertilizer ($kg\ ha^{-1}$)	Available phosphorus ($mg\ kg^{-1}$)
M0	0 N: 0 P_2O_5	6.50
	20.5 N: 23 P_2O_5	8.97
	41 N: 46 P_2O_5	10.04
M 2500	0 N: 0 P_2O_5	5.31
	20.5 N: 23 P_2O_5	15.70
	41 N: 46 P_2O_5	21.12
	Fpr	< 0.001
	Lsd (0.05)	2.03

Appendix 9: Interactive effect of manure and mineral fertilizer on soil total nitrogen in 2014 cropping season

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	Total nitrogen (%)
M0	0 N: 0 P_2O_5	0.033
	20.5 N: 23 P_2O_5	0.032
	41 N: 46 P_2O_5	0.024
M 2500	0 N: 0 P_2O_5	0.026
	20.5 N: 23 P_2O_5	0.032
	41 N: 46 P_2O_5	0.038
	Fpr	0.002
	Lsd (0.05)	0.008

Appendix 10: Interactive effect of water harvesting techniques and organic manure on soil exchangeable potassium in 2014 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	xchangeable K (cmol$_c$ kg^{-1})
C. tillage	M0	0.047
	M 2500	0.049
Tied ridge	M0	0.044
	M 2500	0.062
Zai	M0	0.058
	M 2500	0.054
	Fpr	0.002
	Lsd (0.05)	0.020

C. tillage: Conventional tillage

Appendix 11: Interactive effect of water harvesting techniques and mineral fertilizer on soil exchangeable potassium in 2014 cropping season

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	xchangeable K (cmol$_c$ kg^{-1})
C. tillage	0 N: 0 P_2O_5	0.03
	20.5 N: 23 P_2O_5	0.06
	41 N: 46 P_2O_5	0.05
Tied ridge	0 N: 0 P_2O_5	0.06
	20.5 N: 23 P_2O_5	0.05
	41 N: 46 P_2O_5	0.05
Zai	0 N: 0 P_2O_5	0.04
	20.5 N: 23 P_2O_5	0.06
	41 N: 46 P_2O_5	0.06
	Fpr	< 0.001
	Lsd (0.05)	0.02

C. tillage: Conventional tillage

Appendix 12: Interactive effect of manure and mineral fertilizer on soil exchangeable potassium in 2014 cropping season

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	xchangeable K (cmol$_c$ kg^{-1})
M0	0 N: 0 P_2O_5	0.05
	20.5 N: 23 P_2O_5	0.05
	41 N: 46 P_2O_5	0.05
M 2500	0 N: 0 P_2O_5	0.05
	20.5 N: 23 P_2O_5	0.06
	41 N: 46 P_2O_5	0.06
	Fpr	0.03
	Lsd (0.05)	0.008

Appendix 13: Interactive effect of water harvesting techniques and mineral fertilizer on cation exchange capacity in 2013

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	Cation exchange capacity (cmol$_c$ kg^{-1})
C. tillage	0 N: 0 P_2O_5	4.7
	20.5 N: 23 P_2O_5	6.06
	41 N: 46 P_2O_5	5.85
Tied ridge	0 N: 0 P_2O_5	6
	20.5 N: 23 P_2O_5	5.54
	41 N: 46 P_2O_5	5.03
Zai	0 N: 0 P_2O_5	4.47
	20.5 N: 23 P_2O_5	6.12
	41 N: 46 P_2O_5	7.78
	Fpr	0.009
	Lsd (0.05)	2.32

C. tillage: Conventional tillage

Appendix 14: Interactive effect of water harvesting techniques and manure on pearl millet straw N uptake in 2013 cropping season

Water harvesting techniques	Manure (kg ha^{-1})	Straw N uptake (kg ha^{-1})
Conventional tillage	M0	33.5
	M 2500	32.12
Tied ridge	M0	26.95
	M 2500	29.76
Zai	M0	32.7
	M 2500	43.82
	Fpr	0.003
	Lsd (0.05)	4.9

Appendix 15: Interactive effect of water harvesting techniques and mineral fertilizer on pearl millet grain N uptake in 2014 cropping season

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	Grain N uptake (kg ha^{-1})
		N
Conventional tillage	0 N: 0 P_2O_5	11.83
	20.5 N: 23 P_2O_5	14.49
	41 N: 46 P_2O_5	11.64
Tied ridge	0 N: 0 P_2O_5	13.2
	20.5 N: 23 P_2O_5	18.65
	41 N: 46 P_2O_5	15.95
Zai	0 N: 0 P_2O_5	11.92
	20.5 N: 23 P_2O_5	28.73
	41 N: 46 P_2O_5	17.49
	Fpr	< 0.001
	Lsd (0.05)	4.35

Appendix 16: Interactive effect of water harvesting techniques and mineral fertilizer on pearl millet straw N uptake in 2013 cropping season

Water harvesting techniques	Mineral fertilizer (kg ha^{-1})	ıw N uptake (kg ha^{-1})
C. tillage	0 N: 0 P_2O_5	21.25
	20.5 N: 23 P_2O_5	30.84
	41 N: 46 P_2O_5	46.34
Tied ridge	0 N: 0 P_2O_5	25.03
	20.5 N: 23 P_2O_5	24.81
	41 N: 46 P_2O_5	35.23
Zai	0 N: 0 P_2O_5	37.75
	20.5 N: 23 P_2O_5	33.35
	41 N: 46 P_2O_5	43.67
	Fpr	< 0.001
	Lsd (0.05)	5.84

C. tillage: Conventional tillage

Appendix 17: Interactive effect of water harvesting techniques and manure on partial N balance at 0 - 20 cm depth in 2013 and 2014 cropping seasons

Water harvesting techniques	Manure (kg ha^{-1})	Partial N balance (kg ha^{-1}) 2013	2014
C. tillage	M0	-19.80	-11.00
	M 2500	17.20	34.95
Tied ridge	M0	-15.20	-24.09
	M 2500	16.90	26.81
Zai	M0	-21.80	-16.79
	M 2500	1.60	19.54
	Fpr	0.049	0.012
	Lsd (0.05)	6.12	8.61

C. tillage: Conventional tillage

Appendix 18: Interactive effect of manure and mineral fertilizer on partial N balance at 0 – 20 cm depth in 2013 cropping season

Manure (kg ha^{-1})	Mineral fertilizer (kg ha^{-1})	ial N balance (kg ha^{-1})
M0	0 N: 0 P_2O_5	-25.20
	20.5 N: 23 P_2O_5	-19.50
	41 N: 46 P_2O_5	-12.10
M 2500	0 N: 0 P_2O_5	-8.20
	20.5 N: 23 P_2O_5	17.40
	41 N: 46 P_2O_5	26.60
	Fpr	< 0.001
	Lsd (0.05)	7.71