



IN-SITU WATER HARVESTING TECHNOLOGIES AND FERTILIZER RATES INCREASE MAIZE AND BEAN YIELDS IN THE SEMI-ARID KATUMANI, KENYA †

[LAS TECNOLOGÍAS DE COSECHA DE AGUA IN SITU Y LAS TASA DE FERTILIZANTE AUMENTAN LOS RENDIMIENTOS DE MAÍZ Y FRIJOLES EN EL SEMIÁRIDO KATUMANI, KENIA]

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SUMMARY

Background: Crop production in the arid and semi-arid lands (ASALs) is constrained by erratic rainfall and poor soil fertility. Therefore, climate smart agriculture mechanisms such as *in-situ* rainwater harvesting technologies and recommended fertilizer rates would be vital for ensuring food security. **Objective:** To evaluate selected *in-situ* water harvesting technologies and fertilizer rates on soil water content and yield of maize and beans at KALRO Katumani Research Center in Machakos County, Kenya during the 2019 and 2020 short and long rain seasons, respectively. **Methodology:** The experiment was established in a randomized complete block design with a split-split plot arrangement, replicated three times, with *in-situ* water harvesting technologies comprising of zai pits, ngolo pits, contour furrows and conventional tillage, as the main plots, whereas the split plots were varying rates of fertilizer inputs: Di-ammonium phosphate (DAP), goat manure and control. The split-split plots comprised of maize and beans cropping systems. Soil moisture content was assessed at 4, 8, 12 and 16 weeks after emergence, whilst nutrient uptake, use efficiency and crop yields at physiological maturity. Data was subjected to analysis of variance. **Results:** Soil moisture, maize and beans yields, nutrient uptake and use efficiency were significantly ($p \leq 0.05$) increased by *in-situ* water harvesting technologies and fertilizer inputs. Highest soil moisture content was recorded under zai and ngolo pits and lowest in conventional tillage treatments. Ngolo pits recorded higher maize and beans grain yield. Application of DAP fertilizer increased maize and beans grain yield compared to control. Intercropping maize and beans increased grain yield significantly ($p \leq 0.05$) compared to sole maize and sole beans. **Implications.** There is need for promoting a combination of *in-situ* rainwater harvesting technologies especially ngolo and zai pits with application of DAP+ manure in semi-arid areas where water is scarce coupled with poor soil fertility. **Conclusion:** Ngolo and zai pits increased soil water retention capacity while application of DAP fertilizer led to increased crop yield and the study therefore recommends their adoption within the study area and extrapolation to areas of similar conditions. **Key words:** *in-situ* water harvesting; ngolo pits; zai pits; nutrients uptake; use efficiency.

RESUMEN

Antecedentes: La producción de cultivos en las tierras áridas y semiáridas (ASAL) se ve limitada por la irregularidad de las lluvias y la escasa fertilidad del suelo. Por lo tanto, los mecanismos de agricultura climáticamente inteligente, como las tecnologías de recolección de agua de lluvia *in situ* y las tasas de fertilizante recomendadas, serían vitales para garantizar la seguridad alimentaria. **Objetivo:** Evaluar tecnologías seleccionadas de recolección de agua *in situ* y tasas de fertilizantes sobre el contenido de agua del suelo y el rendimiento de maíz y frijoles en el Centro de Investigación KALRO Katumani en el condado de Machakos, Kenia, durante las temporadas de lluvia corta y larga de 2019 y 2020, respectivamente. **Metodología:** El experimento se estableció en un diseño de bloques completos al azar con un arreglo de parcelas divididas y divididas, replicado tres veces, con tecnologías de recolección de agua *in situ* que comprenden pozos zai, pozos ngolo, surcos de contorno y labranza convencional, como las parcelas principales, mientras que en las parcelas divididas se variaron las tasas de aportes de fertilizantes: Fosfato diamónico (FDA), estiércol caprino y testigo. Las parcelas divididas fueron constituidas por los sistemas de cultivo de maíz y frijol. El contenido de humedad del suelo se evaluó a las 4, 8, 12 y 16 semanas después de la emergencia, mientras que la

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absorción de nutrientes, la eficiencia de uso y el rendimiento de los cultivos en la madurez fisiológica. Los datos se sometieron a análisis de varianza. **Resultados:** La humedad del suelo, los rendimientos de maíz y frijol, la absorción de nutrientes y la eficiencia del uso aumentaron significativamente ($p \leq 0.05$) con las tecnologías de recolección de agua *in situ* y los aportes de fertilizantes. El contenido de humedad del suelo más alto se registró en pozos zai y ngolo y el más bajo en tratamientos de labranza convencional. Los pozos de ngolo registraron un mayor rendimiento de grano de maíz y frijol. La aplicación de fertilizante DAP aumentó el rendimiento de grano de maíz y frijol en comparación con el control. El cultivo intercalado de maíz y frijol incrementó el rendimiento de grano ($p \leq 0.05$) en comparación con el maíz único y el frijol único. **Implicaciones.** Es necesario promover una combinación de tecnologías de recolección de agua de lluvia *in situ*, especialmente pozos ngolo y zai con la aplicación de estiércol DAP+ en áreas semiáridas donde el agua escasea y la fertilidad del suelo es deficiente. **Conclusión:** Los pozos ngolo y zai aumentaron la capacidad de retención de agua del suelo, mientras que la aplicación de fertilizante DAP condujo a un aumento del rendimiento de los cultivos y, por lo tanto, el estudio recomienda su adopción dentro del área de estudio y la extrapolación a áreas de condiciones similares.

Palabras clave: captación de agua *in situ*; pozos de ngolo; pozos zai; absorción de nutrientes; eficiencia de uso.

INTRODUCTION

Rainfed agriculture is the primary source of livelihoods for majority of farmers in sub-Saharan Africa (SSA) (Mechiche-almi and Abdi, 2020). Unfortunately, this sector has been marred with a myriad of challenges including, but not limited to low and poor rainfall distribution, water scarcity, poor soil fertility, high evapotranspiration rates and high nutrient losses through erosion and runoff (Vanlauwe *et al.*, 2017; Mzezewa *et al.*, 2011; Yazar and Ali, 2016; Gikonyo *et al.*, 2022). These challenges have led to low yields, leaving majority of household's food insecure (Rockström *et al.*, 2003; Mutekwa, 2009).

The reduction in yields from farmers' fields demonstrate the need for appropriate agricultural production technologies, innovations and management practices (TIMPS) that are climate smart and geared towards conservation of the little water received in the ASALs, for the farmers to realize increased food production (Nyang'au *et al.*, 2021; Ngetich *et al.*, 2014; Zougamora *et al.*, 2014; Karuku, 2018; Gikonyo *et al.*, 2022).

Among the proposed technologies that have been effective in increasing crop production are the *in-situ* rainwater harvesting technologies such as zai pits, furrow-ridges, tied ridges, earth and stone bunds and mulch ripping (Abubaker *et al.*, 2014; Biazin *et al.*, 2012). These are simple and more affordable technologies that trap and hold rain water where it falls long enough, increasing time for infiltration, delaying the occurrence of severe water stress, thus buffering crops against damage resulting from water deficits (Bayala *et al.*, 2012; Dile *et al.*, 2013; Mudatenguha *et al.*, 2014; Nyamadzawo *et al.*, 2013). Another unique technique is the use of the ngolo cultivation technology, which has been practiced by the Matengo community in Tanzania. This system is characterized by combination of anti-erosion and soil fertility maintenance technique of pits and ridges on steep slopes (Kato, 2001).

Studies have shown that *in-situ* water harvesting technologies increase crop yields. For instance, JICA (1998) reported that maize grain yield increased by 1.3 times in ngolo pits plots compared to those under conventional tillage. A similar experiment at Mt Kilimanjaro indicated 2.3 times higher maize grain yield in ngolo pits compared to those under conventional tillage and 3 times more compared to those under bench terraces. In Ethiopia, Cofie and Amede (2015) reported increased potato and bean yields by 500% and 250%, respectively, as well a 300-700 % increase in crop water productivity in farms with zai pits compared to those without. In Mali, Malesu *et al.* (2006), found out that maize yields under zai pit increased by a factor of 10 compared to conventional tillage.

In as much as these technologies have shown an increase in crop yields, their effectiveness is inefficient unless supplemented with soil fertility amendments. Combining water harvesting technologies with fertilizer inputs create a synergy that increases water and nutrient use efficiency, hence increasing yield (Winterbottom *et al.*, 2013). Miriti *et al.* (2007) observed that tied ridges in combination with integrated nutrient management had the potential to improve crop production in semi-arid eastern 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 for semi-arid areas under the changing climatic conditions.

In order to address these challenges of soil fertility decline, water scarcity and low economic returns, a trial was established in Katumani, Machakos County with the aim of addressing the effects of *in-situ* water harvesting technologies with combined fertilizer inputs on soil moisture content, nutrient uptake, use efficiency and yield of maize and beans.

MATERIALS AND METHODS

Study site

The experiment was conducted at Katumani Research Station of Kenya Agricultural and Livestock Research Organization (KALRO) in Machakos County (Figure 1), 80 km south-east of Nairobi, amid the short and long rain seasons of 2019 and 2020, respectively. The station lies between latitudes 1°35' S and longitude 37°14' E, at an elevation of 1575 meters above sea level. The area falls under agro-climatic zone IV (Jaetzold *et al.*, 2006).

Katumani experiences a bimodal rainfall pattern with the long rains commencing in March and ends in May whereas the short rains occur in November and taper off in January (Recha *et al.*, 2012). The site's average annual rainfall ranges between 450-600 mm (Jaetzold *et al.*, 2006). The mean maximum and minimum temperature are 24.6 and 13.7 °C, respectively. The mean potential evaporation ranges from 1820mm to 1840mm with an estimated evapotranspiration (ET_o) of 1239 mm per year (Gicheru and Ita, 1987).

The predominant soil types are Ferralo-Chromic Luvisols (WRB 2015), having high sand and low clay content, and exhibiting high bulk density (Karuku and Mochoge, 2016; Karuma *et al.*, 2014; Mbayaki and Karuku, 2021a and b; Mbayaki and Karuku 2022)). These soils have low nitrogen mineralization potential, with a pH of 6.3 (Kwena *et al.*, 2018; Karuku and Mochoge, 2018). Crops grown in the area include

maize (*Zea mays*), beans (*Phaseolus vulgaris*), millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), green grams (*Vigna radiata*), pigeon peas (*Cajanus cajan*) cowpeas (*Vigna unguiculata*) and dolichos lablab (*Lablab purpureus*) and mangoes (*Mangifera indica*).

Experimental Design

The experiment was laid out in a split-split plot design with individual treatments arranged in a randomized complete block design (RCBD) and replicated three times.

Treatments

- i. *In-situ* water harvesting technologies namely; zai pits, ngolo pits, contour furrows and conventional tillage as the main plots.
- ii. Fertilizer types and rates; 100 kg/ha Di-ammonium phosphate (DAP), 50 kg /ha DAP + 2.5 t/ha goat manure, 5 t/ha goat manure as the split plots and a control (no input).
- iii. Cropping systems; sole maize, sole beans and maize-bean intercrop as the split-split plots.

The goat manure used had an alkaline pH (>7.0) with a total nitrogen (TN) content of 2.1%, while organic carbon was 6.4 and 7.4%, phosphorus levels were 785 and 730 ppm, while potassium levels were 17.5 and 14.7 cmol/kg, in the manure used during the 2019 SR and 2020 LR seasons, respectively.

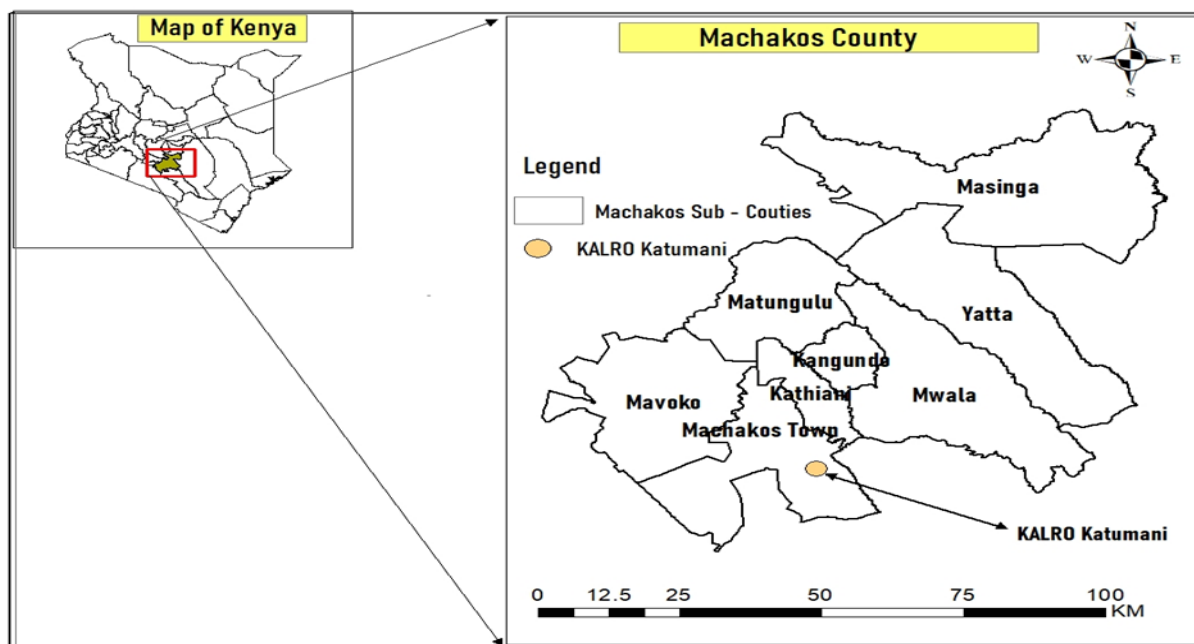


Figure 1. Study site in Machakos county, Kenya.

The blocks measured 15 cm in length and a width of 23 cm. The spacing between main plots was 2 m path, between split plots was 1 m while between the split-split plots was 0.5 m. In each of the split-split plots, there were 3 zai pits under the zai pit technology and three ngolo pits under the ngolo technology. The test crops were maize (Katumani KDV4 variety) and beans (KATB1 variety). These varieties were selected due to their good adaptability, early maturation and yield highly under semi-arid conditions.

Agronomic practices

Land preparation

Land preparation and installation of the rain water harvesting structures was done on 16th October of 2019 before the onset of the short rains. **Zai pits** were constructed by digging a hole measuring 1.5 m × 1.5 m to a depth of 30 cm using a hand hoe (Figure 2a). The top 0-15 cm soil was piled on one side, and that from 15-30 cm piled on the lower side of the pits to trap water in case of runoff, leaving a pit (zai) at the center. The top 0-15 cm dug out soil was then mixed with the fertilizer and manure treatments and returned to half-fill the pit before planting.

Ngolo pits: During the construction of ngolo pits, dried pigeon peas residues were collected, cut into smaller pieces and then spread on the four sides of squares measuring 1.5 m × 1.5 m (Figure 2b). Soil from the center of the pit was heaped evenly on the plant residues, leaving a pit at the center (ngolo) as described by Kato *et al.* (2001). Maize and beans seeds were planted on the heaped soils while the ngolo pits were left bare to collect rain water.

Contour furrows were prepared by digging 0.3 m deep trenches and planting was done in the furrows. The **conventional tillage system** involved preparation of land using hand hoes; which is the farmers practice in the study area.

Crop husbandry

Sowing was done at the onset of the rains on 19th October 2019 and 20th April 2020 for the SR and LR seasons, respectively. Short rain season (SR) commenced in October 2019-February 2020, whereas long rain season (LR) from April 2020-August 2020. Maize was planted at a spacing of 75 cm between the rows and 30 cm within rows, while beans were planted at a spacing of 45 cm between rows and 15 cm within rows. Two maize and three bean seeds were planted per hill, and then thinned two weeks after planting to one maize and two beans per hill, giving a population density of 44,444 maize and 296,296 bean plants per hectare, respectively. Plants were randomly tagged for accuracy and ease of monitoring growth and data collection.

Weeding was done using a hand hoe at the emergence of weeds. At 4 and 8 weeks after emergence. To control black cut worms (*Agrotis ipsilon*), (Duduthrin (Lambdacyhalothrin 17.5g/L) pesticide was sprayed, while corn leaf aphids (*Rhopalosiphum maidis*) were controlled by using Thunder (Imidacloprid 100g/L + Beta-cyfluthrin 45g/L) and Marshal (35 percent Carbosulfan). During the growing season, pesticides were sprayed four times at 14-day intervals.

Beans and maize were harvested at physiological maturity (2 and 4 months), respectively.



A) Zai pits



B) Ngolo pit

Figure 2. These rain water harvesting structures (pits) were left on the land for the preceding long rain season.

Installation of access tubes

The polyvinyl chloride (PVC) access pipe, 100 cm long and 5cm in diameter, with a watertight lid at the bottom, were manually inserted in the auger holes, in the middle of each plot for soil moisture measurement. In the zai pits, the pipes were placed in between the maize crops along the rows. In ngolo pits, pipes were placed on top of the ridges, between the crops, whereas in contour furrows, they were placed inside the furrows. Pipes were placed between the maize crops along the rows in in the middle of the conventional tillage.

Data collection

Weather data

Daily weather data on rainfall (mm), maximum and minimum temperature (°C) was obtained from the meteorological weather station located at the KALRO-Katamani meteorological station.

Soil moisture content

Soil moisture was measured at 4, 8, 12 and 16 weeks after planting (WAP) non-destructively using a calibrated Neutron 503DR Hydro probe. This was calibrated using the gravimetric water content (g/100 g soil) by plotting a graph of neutron counts against gravimetric water content. A line of best fit was developed with,

$$y = mx \times c \quad (1)$$

Where;

y = gravimetric water content, m = the gradient, x = neutron counts and c = y intercept.

All the neutron probe readings were converted into gravimetric by multiplying with m (gradient of the line of best fit). Finally, the gravimetric water readings were converted into volumetric using (Eqn 2)

$$\theta = \omega \rho b \div \rho w \quad (2)$$

Plant tissue sampling and analysis

Beans and maize plant tissue samples were collected 65 and 120 days after sowing when crops attained physiological maturity. Five (5) randomly selected and tagged maize plants were cut at the base with a machete and separated into grains and biomass, whereas ten (10) bean plants were uprooted by hand. Grains were threshed manually and their weights recorded using a weighing balance ($\pm 0.05g$ precision). Three (3) maize Stover and five (5) bean straws from the harvested batch were chopped into smaller pieces.

A subsample of grains and biomass were put in respective khaki bags, and dried in the oven at 70 °C for 24 hours to a constant weight, while beans were sun dried for 3 days to attain a moisture content of 12.5%.

The dried samples were ground using a Willey Mill and passed through a 2 mm sieve for analysis of N, P and K contents using standard procedures as shown in Table 1.

Nutrient uptake

The nutrients (N, P and K) uptake was calculated as a product of nutrient concentration in grains or straw and the yield (Eqn 3).

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \text{nutrient concentration} \times \text{total dry matter yield} \quad (3)$$

Table 1. Laboratory procedures.

Parameter	Method	References
Total nitrogen	Modified micro-Kjeldahl method	Bremner,1996
Available phosphorus	Extracted by Mehlich-1, then measured using a UV spectrophotometer	Murphy and Riley, 1962
Potassium	Flame photometer	Barnes <i>et al.</i> , 1945

Nutrient use efficiency

Nutrient use efficiency was computed using the formula as described by Brentrup and Palliere (2010) (Eqn 4).

$$\text{Nutrient use efficiency} = \frac{\text{Yield in fertilized plots} - \text{yield in control plots}}{\text{the amount of fertilizer applied}} \quad (4)$$

Biomass and grain yield

Final biomass and grain yield were obtained from plants harvested from the net plot measuring 2.25 m² after discarding the border rows and end of plants of each row. The collected subsamples were oven dried at 70 °C for 48 hours. Dry maize and beans grain and Stover/straw were computed using (Eqn 5).

$$\text{Grain/biomass yield (kg ha}^{-1}\text{)} = \frac{\text{Grain dry yield (kg)} \times 10,000 \text{ m}^2}{\text{total area of the plots}} \quad (5)$$

Statistical analysis

Effect of different treatments on soil moisture, yield, nutrient uptake and use efficiency was determined in a two-way ANOVA with the aid of GenStat 15th edition (Lane and Payne, 1997). Mean separation was done using Fisher's protected Least Significant Difference (LSD) at 5% significance level.

RESULTS AND DISCUSSIONS

Soil physical and chemical properties

The soil physical and chemical properties are presented in Tables 2 and 3.

The soil had a sandy clay loam (SCL) textural class, with percentage sand decreasing down the soil profile, whereas clay content increased. Kwena *et al.* (2018) obtained similar findings in the textural class and this may have an implication to water holding and rain water holding issues. Similarly, the diffusivity may be lower and hence availability of nutrients is limited and hence may affect the nutrient use efficiency.

The bulk density was 1.4 g/cm³ at the upper horizon and it decreased down the soil profile. The high bulk density at the top horizon could have formed due to compaction caused by previous shallow ploughing which created an impervious layer and a hard pan. Digging of ngolo and zai pits as well as construction of the contour furrows helped in breaking the surface crust, hence improving water infiltration (Danjuma and Mohammed, 2015). This could be the probable reason for higher soil moisture obtained at deeper horizons under the rain water harvesting technologies, as the technologies collected water and retained it for period of time.

The average soil pH was 6.25, within the range between 5.0 -7.0, required for effective growth of maize and beans (FAO, 2012). Soil pH plays a pivotal role in the chemical characterization of the soil. In most arid and semi-arid areas, a mixture of minerals exists each with different zero point of charge (ZPC)

similar to this study site. A soil is composed of so many constituents that the ZPC value of the soil is determined and/or affected by their physico-chemical properties and eventually its efficiency in crop production (Bennett *et al.*, 2019).

The % OC ranged from 0.6 to 1.2 %, hence low, according to London (2014). Soil organic matter is a key attribute of soil quality that impacts soil aggregation, resulting in increased infiltration, movement of water in the soil and available water capacity. Soils with organic matter content $\leq 3\%$ are considered not suitable for crop production, because the ideal organic matter content is $\geq 6\%$ (USDA, 1997), hence there in need for addition of fertilizers and manure in order to increase crop production.

The TN ranged between 0.08 to 0.1%, hence regarded as low (London, 2014). The low TN could be attributed to the low soil organic carbon, mainly as a result of lack of crop residue plough back. Available phosphorus content ranged between 15 to 23.4 ppm, rated at medium in relation to the threshold value of 25 ppm (Brennan *et al.*, 2013; Fairhurst, 2012). Exchangeable potassium (K) concentration ranged between 0.9 to 1.7 cmol/kg.

Climatic data

Monthly climatic data during crops' growing season are shown in Table 4.

In the 2019 SR, most rainfall was recorded at crop planting (I) and vegetative development stages (II); 219.9 and 211.5 mm, respectively (Figure 3). On the other hand, minimal rainfall was recorded at tasseling/silking stage; 57.9 mm. Low rainfall especially at tasseling/silking stage could result to water stress and therefore affect grain filling process and eventually, yield. However, this was not the case in the 2019 short rain season, probably because of the presence of the *in-situ* water harvesting technologies which could have stored enough soil moisture and availed it to crops for uptake.

Table 2. Soil physical properties of the experimental site.

Depth	Pb (g/cm ³)	Porosity %	Sand %	Clay %	Silt %	Ksat cm/hr	Textural class
0-15	1.4	0.47	74	24	2	19.6	SCL
15-30	1.2	0.55	70	28	2	43.5	SCL
30-45	1.2	0.55	68	30	2	36.1	SCL
45-60	1.2	0.55	66	32	2	32.8	SCL
60-75	1.2	0.55	64	32	4	37.4	SCL
75-90	1.3	0.51	62	34	4	9.1	SCL
Average	1.25	0.53	69	29	3	29.8	SCL

Legend: Pb- Bulk density, SCL- Sandy clay loam.

Table 3. Soil chemical properties.

Parameters	0-15 cm	15-30 cm	30-60 cm	75-90 cm
pH (H ₂ O)	6.6	6.5	6.1	5.80
Organic carbon (OC) (%)	1.2	1.3	0.9	0.55
Total Nitrogen (TN) (%)	0.1	0.1	0.1	0.08
Phosphorus (P) (ppm)	23.4	25.1	23.9	15.00
Potassium (K) (cmol/kg)	1.7	1.9	1.8	0.90

In the 2020 LR, minimal rainfall was recorded at crop vegetative development, tasseling/silking and at maturity; 12, 6.3 and 5 mm, respectively. The highest rainfall experienced was at initiation (I); 140.8 mm.

On average, the two cropping seasons recorded low rainfall, though higher in short rain season than in the long rain season (Figure 3). Low rainfall in the 2020 LR season would imply that crop yields would be lower as uptake of water and nutrients by plant roots would be difficult as water is held at high tension meaning more energy expended in water uptake that could go to yield production.

Reference evapotranspiration was higher during the 2020 LR season compared to the 2019 SR season, with higher values recorded at tasseling/silking (III) and maturation (IV) stages compared to values recorded at vegetative/development (II) and at initiation (I) stages (Figure 3).

The increase in the ETo values coincided with tasseling and silking stages where the rate of transpiration because at this stage, the plants are fully developed. If not managed well, the crops might wilt due to higher water loss because in this period, the water demand is the greatest and therefore, a strict control of water supply is quite necessary (Farias *et al.*, 2017).

The average maximum and minimum temperature recorded in the 2019 SR was 25 and 15.1 °C, respectively. The hottest months were February and March, corresponding to crop maturation stages with a mean temperature of 26.2 °C. In the 2020 LR, the average maximum air temperature was 24.4 and minimum was 12.7 °C, with May and June as the hottest months with maximum mean temperature of 24.8 and minimum temperature of 13 °C.

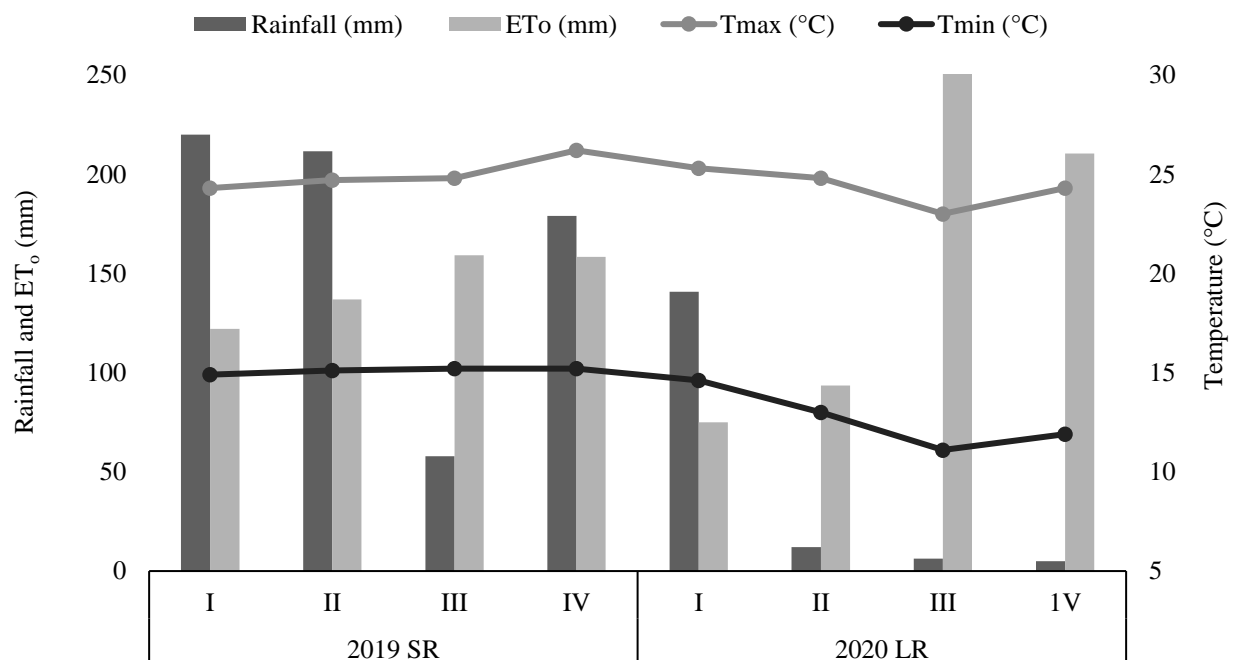


Figure 3. Rainfall, reference evapotranspiration (ET₀), minimum (Tmin) and maximum (Tmax) temperature recorded for different maize development stages namely; initiation (I), vegetative and development (II), tasseling/silking (III) maturation (IV).

Influence of *in-situ* water harvesting technologies, fertilizer inputs and cropping systems on soil moisture retention

Table 4 presents soil moisture content (cm^3/cm^3) at different sampling times. Soil moisture recorded at 4 weeks after planting (WAP) showed significant ($p \leq 0.05$) differences among the *in-situ* rain water harvesting technologies. Ngolo pits recorded $22.87 \text{ cm}^3/\text{cm}^3$ moisture, significantly higher than contour furrows and conventional tillage which recorded 19.45 and $16.42 \text{ cm}^3/\text{cm}^3$, respectively. The higher and significant soil moisture observed in ngolo pits compared to the other technologies could be attributed to the increased water retention as well as the mulching effect resulting from the buried crop residues during construction. These findings are consistent with those of Malley (2005) who found out that the buried residues in the ngolo pits, helped in improving soil fertility status, conserved soil moisture and led to increased maize yield.

A similar trend was observed in the soil moisture recorded at 8 WAP (tasselling and silking stage).

At this stage, crops had fully developed and the ground cover was sufficient to reduce the direct impact of solar

radiation which helped in reducing soil evaporation rate (Qi *et al.*, 2011). Well established crop cover can also increase water infiltration and reduce runoff (Yu *et al.*, 2016). This could have been attributed to the reduced ET_0 as reported earlier.

Similarly, cropping systems had a significant ($p \leq 0.05$) effect on soil moisture between cropping at crop vegetative development stage (4 WAP) and tasselling/silking stages (8 WAP). Sole plots of maize and beans recorded; 18.01 and $18.97 \text{ cm}^3/\text{cm}^3$ moisture, respectively at 4 WAP and 11.08 and $12.36 \text{ cm}^3/\text{cm}^3$ moisture, respectively at 8WAP compared to intercrop.

Comparison of soil moisture between seasons and treatments showed that 2019 SR season was higher compared to the 2020 LR. This could be attributed to the differences in the amount of rainfall received, with the 2020 LR season, receiving only 309 mm the entire growing season, which is below the maize and beans water requirement of 500-800 and 300-500 mm, respectively (FAO, 2012; Abideen, 2014). This was a limiting factor in contrast to the 2019 SR season where the total rainfall received was 1078 mm. This implied that crops did not suffer water stress during the 2019 season, hence the higher yields recorded.

Table 4. Influence of *in-situ* water harvesting technologies, fertilizer inputs and cropping systems on soil water content in cm^3/cm^3 at the top 0-20 cm depth.

Treatments	2019 SR				2020 LR			
	4 WAP	8 WAP	12 WAP	16 WAP	4 WAP	8 WAP	12 WAP	16 WAP
Water harvesting technologies (T)								
Ngolo pits	22.87 ^a	14.75 ^a	17.21 ^a	16.78 ^a	14.97 ^a	13.40 ^{ab}	14.76 ^a	14.21 ^a
Zai pits	20.15 ^{ab}	13.14 ^{ab}	17.12 ^a	16.71 ^a	13.82 ^a	13.78 ^a	15.49 ^a	15.16 ^a
Contour furrows	19.45 ^b	11.22 ^b	15.43 ^a	16.20 ^a	13.72 ^a	12.24 ^b	14.50 ^a	14.82 ^a
Conventional tillage	16.42 ^c	10.91 ^c	14.74 ^a	16.10 ^a	13.64 ^a	11.58 ^b	13.41 ^a	11.02 ^a
Fertilizer inputs (I)								
DAP	18.80 ^a	11.15 ^a	17.30 ^a	17.10 ^a	14.17 ^a	12.41 ^a	14.75 ^a	13.77 ^a
½ DAP + ½ Manure	19.30 ^a	12.15 ^a	15.97 ^{ab}	16.53 ^a	14.22 ^a	12.49 ^a	14.86 ^a	13.72 ^a
Manure	17.99 ^a	11.05 ^a	15.77 ^b	16.25 ^a	13.99 ^a	12.48 ^a	14.29 ^a	14.39 ^a
control	16.34 ^a	11.01 ^a	15.47 ^b	16.00 ^a	13.85 ^a	12.22 ^a	14.26 ^a	13.34 ^a
Cropping systems (CS)								
Sole beans	18.97 ^a	12.36 ^a	16.68 ^a	16.61 ^a	14.93 ^a	12.17 ^a	14.42 ^a	13.32 ^a
Sole maize	18.01 ^a	11.08 ^{ab}	15.91 ^a	16.47 ^a	13.91 ^a	12.56 ^a	14.45 ^a	13.00 ^a
Intercrop	16.44 ^b	10.57 ^b	15.79 ^a	16.34 ^a	13.33 ^a	12.49 ^a	14.75 ^a	15.10 ^a
Summary <i>p</i>-values								
T	0.002	0.008	0.172	0.940	0.046	0.006	0.507	0.346
I	0.157	0.311	0.014	0.474	0.549	0.710	0.824	0.671
CS	0.037	0.029	0.288	0.814	0.105	0.239	0.836	0.006
I × CS	0.054	0.558	0.151	0.082	0.624	0.929	0.975	0.623
T × CS	0.389	0.306	0.546	0.188	0.091	0.904	0.281	0.944
T × I × CS	0.038	0.406	0.656	0.629	0.207	0.434	0.349	0.614

Legend: DAP fertilizer (100 kg/ha), half rate DAP + half rate goat manure (50 kg /ha+2.5 t/ha), Manure (5 t/ha), WAP-Weeks after planting *Means followed by the different letter down the column differ significantly at $p \leq 0.05$

The difference in soil moisture content at different growth stages could be attributed to the amount of rainfall, soil evaporation, transpiration and crop water uptake (Mujdeci *et al.*, 2010). For instance, low soil moisture was recorded at tasselling stage (8 WAP) and silking (12 WAP) compared to vegetative development stage (4 WAP). Tasselling and silking are the critical stages where crops water requirement is high and therefore takes up a lot of water from the soil. Moisture stress and nutrient deficiencies occurring at these stages could greatly reduce the number of kernels per row, resulting in shorter ears and lower yield potential (Admasu *et al.*, 2017).

Formation of pits during the construction of ngolo and zai technologies allowed more storage of rain water and time for infiltration, thus the reason for higher soil moisture content. One proven attribute of ngolo pits is soil entrapment in the pits, which helps in reducing runoff whilst encouraging infiltration and sedimentation.

Amede *et al.* (2011), Milkias *et al.* (2018) and Gebreegziabher *et al.* (2009), recorded higher soil moisture content in zai pits and tied ridges probably due to increased water retention, infiltration and reduced run-off. Fatondji *et al.* (2006), while working on psammentic paleustalf soils in Niger reported similar findings with zai pits retaining significantly more soil water than conventional tillage.

The low soil water content recorded in intercrop system compared to monocrops could be due to the high population density per plot, which could have resulted in higher water extraction from the soil. These findings are in conformity with those of Karuma *et al.* (2014), while working on Alfisols and Acrisols soil types in the semi-arid area of Mwala in Machakos county.

Beans provided soil cover during the vegetive and development stages, a probable reason for higher soil moisture in bean plots. Steiner (2002) reported that cropping systems that offer surface cover promote soil water conservation by reducing evaporation and increasing infiltration rate.

Maize grain and biomass yields

Table 5 presents the interactive effects of water harvesting technologies, fertilizer inputs and cropping systems on maize grain and Stover yields.

In-situ water harvesting technologies, fertilizer inputs and cropping systems significantly ($p \leq 0.05$) improved maize grain yield during the 2019 SR

season. Highest maize grain yield (4.5 t/ha) was obtained in ngolo pits, which was 28.5, 44 and 68.6 % higher than zai pits, contour furrows and conventional tillage, respectively (Table 3). While there was no significant difference between maize yields in zai pits and contour furrows, mean separation indicated that zai pits had 21.7% more yield than contour furrows.

Application of fertilizer and manure resulted in a significant ($p \leq 0.05$) maize yield increase with following trend; DAP \geq DAP + 2.5 t/ha manure \geq 5 t/ha of manure \geq control treatments. Significant differences ($p < 0.001$) in maize grain yield were also observed between cropping systems, where maize yield was higher in the intercrop compared to sole maize. This could be attributed to the increased water and nutrient use efficiency and the complementarity between the two crops as alluded by Hauggaard-Nielsen *et al.* (2008) and Buhk *et al.* (2017).

Similar trend was observed in stover production, with *in-situ* rain water harvesting technologies having a significant ($p \leq 0.05$) effect. Highest stover of 7.43 t/ha was recorded in ngolo pits, which was significantly different from stover obtained from contour furrows and conventional tillage which recorded the least stover of 4.39 and 3.16 t/ha, respectively. Application of DAP fertilizer gave the highest stover yield with control plots yielding the lowest stover.

In the 2020 LR season, the effect of fertilizer inputs was significant ($p < 0.001$) in influencing maize grain and stover yields. The highest mean yields were recorded in plots treated with DAP alone and in combination with manure at half rates, with the lowest in the control. This could therefore imply that addition of organic and inorganic amendments to the soil improved the chemical properties that enhanced availability of nutrients and their uptake as alluded by Ruganzu *et al.* (2015).

Moisture content plays a pivotal role in crop's physiological development from germination to maturity as it controls crop's phenological, physiological and morphological characteristics (Khan *et al.*, 2001). When there is soil water scarcity, the number of grains per plant and yield per unit area also declines (Saberina, 2010). This is because the biochemical processes occurring in the plant are affected and the crops tend to hasten their maturity and can end up wilting. Higher grain and stover yields observed in ngolo and zai pit technologies could be attributed to the nutrient and moisture availability. Crop roots absorb these available resources, resulting in increased growth and improved grain yield.

Table 5. Maize Stover and grain yields as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems.

Treatments	2019 SR		2020 LR	
	Stover	Grains	Stover	Grains
t/ha				
Water harvesting technologies (T)				
Ngolo pits	7.43 ^a	4.52 ^a	4.21 ^a	1.55 ^a
Zai pits	5.98 ^{ab}	3.23 ^b	2.65 ^a	1.06 ^a
Contour furrows	4.39 ^{bc}	2.53 ^b	3.47 ^a	0.88 ^a
Conventional tillage	3.16 ^c	1.42 ^c	2.24 ^a	0.61 ^a
S.E.	0.528	0.248	0.527	0.303
LSD \leq 5%	1.827	0.574	2.5824	1.048
Fertilizer inputs (I)				
DAP	7.20 ^a	3.67 ^a	4.81 ^a	1.54 ^a
½ DAP + ½ Manure	5.66 ^b	3.49 ^a	3.49 ^b	1.25 ^a
Manure	5.09 ^b	2.53 ^b	2.51 ^c	0.87 ^b
Control	3.01 ^c	2.02 ^c	1.74 ^d	0.44 ^c
S.E.	0.233	0.145	0.179	0.121
LSD \leq 5%	0.681	0.323	0.522	0.353
Cropping system (CS)				
Sole maize	5.01 ^b	2.88 ^b	2.97 ^b	0.97 ^a
Maize-bean intercrop	5.36 ^a	3.21 ^a	3.31 ^a	1.08 ^a
S.E.	0.118	0.069	0.081	0.051
LSD \leq 5%	0.339	0.132	0.234	0.146
Summary of <i>p</i> -values				
T	0.006	<.001	0.134	0.234
I	<.001	<.001	<.001	<.001
CS	<.001	<.001	0.024	0.124
T×CS	0.685	0.330	0.151	0.500
T×I	0.008	0.058	0.090	0.050
I×CS	0.659	0.659	0.017	0.045
T×I×CS	0.439	0.467	0.477	0.997

Legend: DAP fertilizer (100 kg/ha), half rate DAP + half rate goat manure (50 kg/ha+2.5 t/ha), Manure (5 t/ha)¹, *Means followed by the different letter down the column differ significantly at $p \leq 0.05$

Kumar *et al.* (2000) observed that availability of moisture in the soil during crop growth stages resulted in better crop growth and improved yield. Mudatenguha *et al.* (2014) linked the significant increase in maize yield under zai pits compared to conventional tillage to, the ability of zai pits to collect, store and avail soil moisture to the crop roots during growth.

JICA (1998) attributed the higher maize yields recorded under ngolo pits to improved soil fertility status, which could have resulted from decomposition of the buried crop residues during the construction of pits.

According to Kato (2001), darker soil rich in organic matter is formed in deeper layers under ngolo pits, when buried residues are mixed into the deep soils, which provide conditions favorable for high crop yields (Kato, 2001).

These results are consistent with Wouterse (2017) who reported that zai pit technology was an intervention used by smallholder farmers to increase agricultural production through improving rainwater capture, reducing runoff, reducing water evaporation from the soil increasing water infiltration. Biazin *et al.* (2012), Danjuma *et al.* (2012) and Kar *et al.* (2013) also reported that rain water harvesting technologies in combination with the use of inorganic and organic inputs increases nutrients in the soil, thereby improving crop productivity.

The significant increase in grain and biomass yield in response to the application of DAP fertilizer alone and mixture of DAP and manure at half rates could be attributed to increased nutrient and soil moisture availability, which could have facilitated the uptake of nutrients by plant roots, translating to high yield. Soil moisture has an impact on the forms, solubility, and accessibility of plant nutrients required for crop growth (Ampofo, 2006). Increased yield following fertilizer

and manure application could be attributed to the improved fertility status of the soil, as alluded by Patel *et al.* (2013). This result signified the more prominent roles played by DAP fertilizer and manure in enhancing growth of crops and thus yield. This is due to the fact that mineral fertilizer provides nutrients that are easily soluble in soil solution, whereas organic manures help to improve soil health and health, thereby improving nutrient availability and making nutrients readily available to crops (Aziz *et al.*, 2010; Ayuke *et al.*, 2004; Bationo, 2004).

Under cropping systems, grain and stover yields from intercropping systems outperformed those from monocrop. This implies that intercropping is more efficient than mono-cropping at utilizing soil water and nutrients, which could be attributed to intercrop complementarity and synergist effects. This contradicts the findings of Belel *et al.* (2014), who obtained lower yields in intercropping systems due to competition for moisture, nutrients and light.

Lower maize grain and stover yields were recorded in 2020 long rains in all the treatments, which could be attributed to the low amounts of rainfall received during the season (Figure 1). Given that maize requires 500-800 mm of water in the entire growing season (FAO, 2012), the rainfall amount recorded in this season was inadequate to meet the crop's seasonal water requirement. This might have resulted in water stress conditions, which might have resulted in reduced nutrient uptake, growth and yield (Khondaker *et al.*, 2013).

Bean grain yield

The interactive effects of *in-situ* water harvesting technologies, fertilizer inputs and cropping systems on bean yields is shown in Figure 4.

Bean yield was significantly ($p \leq 0.05$) affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems. A significant ($p \leq 0.05$) interaction between water harvesting technologies \times fertilizer inputs \times cropping system was observed. Higher grain yield of 1.64 t/ha was obtained in bean-maize intercropping system under ngolo pits following the application of 100 kg/ha DAP fertilizer, whereas lowest yield of 0.44 t/ha was obtained from control plots of sole beans under conventional tillage during the 2019 SR (Figure 4).

During the 2020 LR, rainfall distribution was poor, with prolonged drier conditions experienced throughout the growing season, and this greatly affected beans, resulting to crop failure.

These results show that combination of *in-situ* water harvesting technologies; ngolo pits and DAP fertilizer favored beans growth through provision of water and nutrients for uptake, and thus improved yield. Under the different cropping system, higher yield was observed under the intercrop system. This could be attributed to the complementarity and synergist effects between intercrops.

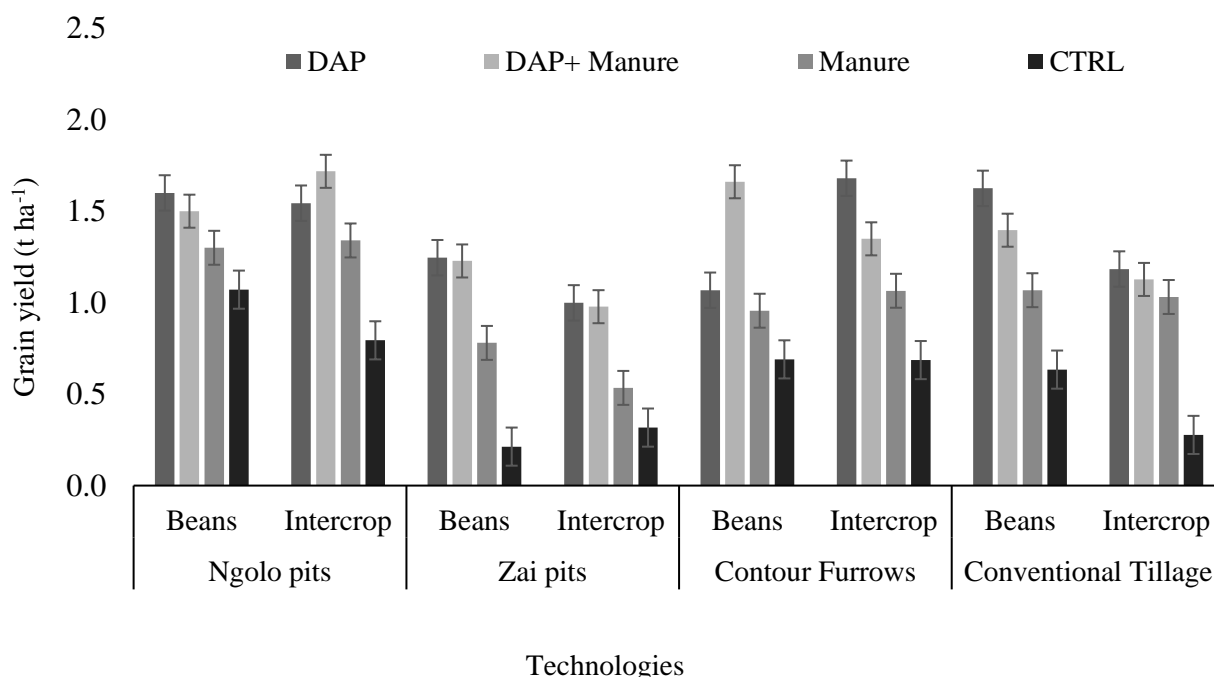


Figure 4. Bean grain yield as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems.

Drought experienced during the 2020 LR especially at the crop flowering stage could have resulted in significant reduction in crop growth and hence low dry matter production. The drying of leaves signifies a reduction in photosynthesis the pathways, hence low leaf development and reduced light interception. This in turn results to a significant reduction in yields (Emam *et al.*, 2010). Similar findings were presented by Rezene *et al.* (2013) who reported that drought stress at the pre-flowering resulted to a reduction in seed quality, lowered the number of pods per bean plant, ultimately leading to a reduction in yields.

Effect of *in-situ* water harvesting technologies, fertilizer inputs and cropping systems on nutrient uptake

The interactive effect of water harvesting technologies, fertilizer inputs and cropping systems on nutrient uptake is shown in Table 6.

In-situ water harvesting technologies, fertilizer inputs and cropping systems had significant ($p \leq 0.05$) effects on grain N, P and K uptake. In the SR, the highest grain N, P and K uptake by maize grain (67.7, 48.2 and 24.9 kg/ha, respectively) recorded in ngolo pits were significantly different from zai pit, contour furrows and conventional tillage. The lowest uptake by grain were exhibited in conventional tillage (Table 6).

Highest N, P and K content was recorded following application of DAP fertilizer, with control plots exhibiting the lowest grain N, P and K contents. Application of 100 kg/ha DAP fertilizer recorded 31.8, 29.6 and 31.6% higher N, P and K, respectively than application of 5 t/ha manure and 56.3, 53.2 and 54.5% higher N, P and K uptake, respectively than control plots.

Table 6. Nutrient uptake in maize grain as affected by water harvesting technologies, fertilizer inputs and cropping systems

Treatments	2019 short rain (SR)			2020 long rain (LR)		
	Grains uptake (Kg/ha)			Grains uptake (Kg/ha)		
	N	P	K	N	P	K
Water harvesting technologies (T)						
Ngolo pits	67.7 ^a	48.2 ^a	24.9 ^a	23.2 ^a	20.1 ^a	12.1 ^a
Zai pits	43.1 ^b	40.7 ^{ab}	16.2 ^b	15.9 ^a	19.0 ^a	10.9 ^a
Contour furrows	38.9 ^b	35.2 ^b	12.5 ^b	11.2 ^a	11.7 ^a	10.0 ^a
Conventional tillage	19.5 ^c	25.7 ^c	9.5 ^c	11.2 ^a	11.3 ^a	7.4 ^a
S.E.	3.180	2.07	0.913	3.432	2.131	1.011
LSD $\leq 5\%$	11.003	10.62	3.527	11.878	7.374	5.119
Fertilizer inputs (I)						
DAP	55.4 ^a	42.5 ^a	20.9 ^a	20.9 ^a	19.9 ^a	13.3 ^a
½ DAP + ½ Manure	51.7 ^a	37.1 ^a	18.5 ^b	18.3 ^{ab}	17.6 ^a	10.4 ^a
Manure	37.8 ^b	29.9 ^b	12.5 ^c	14.3 ^b	15.6 ^a	7.6 ^{ab}
control	24.2 ^c	19.9 ^b	9.5 ^d	8.0 ^c	9.1 ^b	4.3 ^b
S.E.	3.531	2.81	0.887	1.505	1.697	0.988
LSD $\leq 5\%$	10.307	11.13	2.076	4.394	4.953	4.729
Cropping systems (CS)						
Sole maize	38.8 ^b	43.2 ^b	14.2 ^b	14.5 ^a	15.1 ^a	12.2 ^a
Maize-bean intercrop	45.8 ^a	56.5 ^a	16.6 ^a	16.2 ^a	16.0 ^a	12.8 ^a
S.E.	1.264	1.71	0.137	0.823	0.556	0.412
LSD $\leq 5\%$	3.64	4.92	0.711	2.371	1.603	0.945
Summary p-values						
T	<.001	<.001	<.001	0.136	0.048	0.079
I	<.001	<.001	<.001	<.001	0.001	0.034
CS	<.001	<.001	<.001	0.155	0.238	0.122
T × I	0.196	0.084	0.008	0.019	0.260	0.312
T × CS	0.473	0.469	0.056	0.243	0.038	0.541
I × CS	0.364	0.200	0.728	0.870	0.719	0.119
T × I × CS	0.264	0.633	0.124	0.979	0.742	0.674

Legend: DAP fertilizer (100 kg/ha), half rate DAP + half rate goat manure (50 kg/ha+2.5 t/ha), Goat manure (5 t/ ha).

*Means followed by the different letter down the column differ significantly at $p \leq 0.05$.

Cropping systems significantly ($p \leq 0.05$) affected grain uptake, with higher N, P and K uptake recorded in intercropped plots than in sole maize plots.

During the LR, *in-situ* water harvesting technologies and cropping systems did not significantly influence N, P and K uptake, however the N, P and K grain contents differed significantly ($p \leq 0.05$) with fertilizer inputs. Application of 100 kg ha⁻¹ DAP fertilizer led to significantly higher N, P and K content than N, P and K contents recorded in control plots.

Nitrogen, phosphorus and potassium values were significantly higher in ngolo as compared to zai pits, contour furrows and conventional tillage, probably due to availability of soil moisture and better root growth that favored nutrient uptake. Water is critical in determining a plant's ability to absorb nutrients from the soil, because, soil water content influences nutrient movement from the soil, to the roots and to the aboveground part of the plants (Rani *et al.*, 2020; Li *et al.*, 2009). Outarra *et al.* (2006) reported a positive correlation between soil moisture and N, P and K uptake due to improved soil moisture status which increases the availability of nutrients. Similar findings were reported by Dougbedji (2002) who found that zai pits improved nitrogen uptake compared to conventional tillage on psammentic paleustalf soils in Niger.

The higher uptake of N, P and K in ngolo pits compared to contour furrows and conventional tillage could be attributed to the improved soil health status due to the decomposition of the buried crop residues. Malley (2005) reported that incidences where soil fertility status is improved, then nutrients are readily available to crops, hence an increased uptake. These findings corroborate with those of Pasley *et al.* (2019), who reported higher N, P and K uptake as a result of increased fertility status.

The results show that adding DAP and manure had a positive response to N, P and K uptake and it was high in plots treated with 100 kg ha⁻¹ DAP followed by mixture of 50 kg ha⁻¹ DAP + 2.5 t ha⁻¹ manure. This might be due to the increased supply of all nutrients directly through organic and inorganic sources to crops. This proposition is consistent with that of Haile *et al.* (2012), who reported that N, P and K uptake by wheat crop was significantly increased when the highest dose of N fertilizer was applied. Similar findings were reported by Malo and Ghosh (2019) who reported highest uptake of N, P and K by rice following the application of inorganic and organic fertilizers.

It was also noted that uptake of N, P and K increased under combined use of *in-situ* water harvesting technologies and fertilizer inputs. This could be attributed to the conserved soil moisture which might

have helped in dissolving the soil nutrients from the applied DAP fertilizer, making them easily available for plant uptake.

During dry season, soils become dry and therefore, plants experience difficulty absorbing nutrients, because most nutrients are in elemental forms rather than ionic forms, resulting in low uptake and hence nutrient levels may be lower than normal (Liu *et al.*, 2013; Jones *et al.*, 2011). This could explain why there was higher nutrient uptake in the 2019 short rains as compared to 2020 long rains. These findings are consistent with the findings of Ademba *et al.* (2014), who reported that N, P, and K uptake varied seasonally due to variation in rainfall patterns. Thus, weather conditions have a significant impact on a plant's ability to absorb nutrients, with low uptake occurring during seasons with insufficient rainfall (Ibrahim *et al.*, 2011; Sigunga *et al.*, 2002).

Effect of *in-situ* water harvesting technologies, fertilizer inputs and cropping systems on nitrogen and phosphorus use efficiency

Table 7 presents the effects of water harvesting technologies, fertilizer inputs and cropping systems on N and P use efficiency.

Nitrogen and phosphorus use efficiency showed significant ($p \leq 0.05$) response to the main effects of *in-situ* water harvesting technologies and fertilizer inputs but not with cropping systems in the 2019 SR season. Nitrogen and phosphorus use efficiency were 30.12 and 38.3 kg/ha under ngolo pits, significantly higher than 12.4 and 16.9 kg/ha N and P use efficiency under conventional tillage in the 2019 SR season (Table 7). No significant difference in N and P use efficiency was recorded between ngolo, zai pits and contour furrows.

Applying DAP fertilizer at 100 kg/ha, led to an increase in N and P use efficiency, whereas application of 5 t/ha manure resulted in lower N use efficiency. Nitrogen and phosphorus use efficiency under DAP alone and mixture of DAP + manure showed an average of 57.4 and 41.9 % increase, respectively over manure alone in the 2019 SR season.

In the 2020 LR, neither *in-situ* water harvesting technologies nor cropping systems were significant in influencing N and P use efficiency. However, fertilizer inputs had a significant ($p \leq 0.05$) on N and P use efficiency. The highest values of N and P use efficiency at 39.1 and 40.1 kg/ha, respectively were obtained following application of 100 kg ha⁻¹ DAP fertilizer, and lowest N and P use efficiency values recorded in plots treated with 5 t/ha manure. Combination of DAP and manure applied at half rates

Table 7. Nitrogen and phosphorus agronomic use efficiency in maize cropping system under *in-situ* water harvesting technologies, fertilizer inputs and cropping systems.

Treatments	2019 SR		2020 LR	
	NUE	PUE	NUE	PUE
Water harvesting technologies (T)				
Ngolo pits	30.16 ^a	38.27 ^a	21.11 ^a	26.42 ^a
Zai pits	24.39 ^a	34.18 ^a	12.04 ^a	14.55 ^a
Contour furrows	25.89 ^a	32.60 ^a	10.80 ^a	12.05 ^a
Conventional tillage	12.44 ^b	16.92 ^b	10.04 ^a	13.14 ^a
S.E.	2.93	3.70	2.13	1.93
LSD \leq 5%	10.14	12.8	8.708	13.06
Fertilizer inputs (I)				
DAP	39.09 ^a	40.05 ^a	22.97 ^a	24.47 ^a
½ DAP + ½ Manure	23.93 ^b	35.90 ^a	15.39 ^b	17.98 ^a
Manure	16.64 ^c	23.28 ^b	13.20 ^c	10.92 ^b
Control	-	-	-	-
S.E.	2.19	2.95	1.93	1.23
LSD \leq 5%	6.55	8.84	4.941	7.006
Cropping system (CS)				
Sole maize	22.5 ^a	29.4 ^a	13.28 ^a	16.86 ^a
Maize-bean intercrop	23.9 ^a	30.1 ^a	14.43 ^a	17.72 ^a
S.E.	1.96	2.53	1.01	1.44
LSD 5%	5.72	7.39	2.464	3.182
Summary <i>p</i>-values				
T	0.024	0.014	0.100	0.131
I	<.001	<.001	<.001	0.008
CS	0.613	0.845	0.347	0.585
T \times CS	0.214	0.230	0.150	0.524
T \times I	0.345	0.368	0.406	0.365
I \times CS	0.705	0.916	0.639	0.817
T \times I \times CS	0.894	0.968	0.579	0.856

Legend: DAP fertilizer (100 kg/ha), half rate DAP + half rate goat manure (50 kg/ha+2.5 t/ha), Goat manure (5 t/ha). NUE-Nitrogen use efficiency, PUE- Phosphorus use efficiency *Means followed by the different letter down the column differ significantly at $p \leq 0.05$.

led to 14.2% increase in N use efficiency compared to when manure was applied at 5 t/ha.

The higher N and P agronomic use efficiencies denoted by yields under ngolo and zai pits than in conventional tillage is a probable indication that there was better utilization of nutrients and water in the two technologies. Crops under these technologies could have benefited from the conserved water and available nutrients at the root zone, which resulted in faster growth, higher nutrient uptake, enhanced utilization and yield. Availability of moisture directly influences the ability of crops to take up nutrients from the soil, and in turn their utilization efficiency. Dougbedji (2002) reported similar findings, where the concentration of N in pearl millet grain was higher under zai pits compared to conventional tillage.

In line with the present finding, Shaheen *et al.* (2012) reported that the efficiency of plants to absorb nutrients and the capacity of the soil to supply them are reduced

under low soil moisture condition, and therefore in agreement with this study's findings.

The beneficial effect of fertilizers in enhancing nutrient use efficiency of crops could be attributed to the rapid early growth, which contributes significantly to dry matter accumulation and hence higher use efficiency (Kugedera *et al.*, 2019). This could probably be the reason for increased N and P use efficiency following application of 100 kg/ha DAP and mixture of 50 kg/ha + 2.5 t/ha manure. Higher uptake and use efficiency contribute to better use of applied nutrients and reduce losses from the soil (Oo *et al.*, 2010).

CONCLUSIONS

Zai and ngolo pits recorded consistently higher soil moisture content at all the sampling times across the two seasons compared to conventional tillage.

Grain and biomass yield as well as nutrient uptake and use efficiency from zai and ngolo pits were higher than those from contour furrows and conventional tillage. It was noted that grain and biomass yield in plots treated with 100 kg/ha DAP fertilizer was not significantly different from those obtained from plots treated with a mixture of 50 kg/ha DAP + 2.5 t/ha goat manure. Farmers can therefore apply a mixture of mineral fertilizer and animal manure at half rates to obtain optimal yield.

Cereals and legumes are recommended to be grown under ngolo or zai pits. This is due to the ability of the two technologies to store water that will be available to crops and to cushion crops against droughts that are predicted to become more frequent and severe as a result of climate change.

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