Effect of water conservation technologies on water use efficiency of green gram pearl millet intercropping system in semi-arid Kenya.

Abstract

The insufficientandinadequatesoilmoisture content in Kenyan's arid areashas steadily reduced in cropproduction. A field experiment was conductedduring 2022/2023 short rain season toevaluatetheeffectofwater harvesting technologies and cropping systems onsoilmoisturedynamics and wateruseefficiency of selected pearl millet and green gram varieties planted in sole and intercrop system inKambi-Mawe and Katumani research stations. The experiment was arranged in a split-plot design with individual treatments arranged in a randomized complete block design, replicated three times. The main plots comprised of water harvesting technologies (ngolo pits, contour furrows) conventional tillage as a control. The cropping system included sole cropping of pearl millet (PMI, PM3), sole green gram varieties (N26 and Biashara) and their intercrops. Soilsampleswerecollectedat the depth of 0-20, 20-40 and 40-60 cmat30 days, 45 days and 60 days after crop emergence and transported to laboratory for fresh weight determination. They were oven dried at 105 ^{o}C for 48 hours and the dry weight recorded. Water use efficiency (WUE) was calculated using Seasonal crop evapotranspiration (ET) and crop yield. Collected data was analysed usingGenStatstatisticalsoftware 15th edition while mean separation was doneusing Tukey HSDat $p \leq 0.05$ significance level. Results illustrated thatwater harvesting technologiesandcropping systemsignificantly increasedthesoilmoisturecontent recorded at different sampling times. Generally, significantlyhighersoilmoisturewasrecordedin ngolo pits,followedby contour furrows, while conventionaltillage recorded relatively lower soil moisture. Plots under intercropping systems recorded lower soil moisture compared to those under sole cropping irrespective of the crops. Higher WUE values were recorded in ngolo pits, and conventional tillage recorded lowest values.

Key words: Arid and semi-arid lands, Water conservation Technologies, intercropping system, Water use efficiency, soil moisture.

Introduction

Water scarcity and shortages have become global issues that have resulted in losses and limitations in agricultural productivity (Wang et al., 2016). The challenge is exacerbated by climate change and greater variability. Despite climatic constraints, conservation agriculture holds promise as it minimizes soil disturbances and ensures efficient conservation of soil moisture (Zaria, 2011). Intensive tillage practices and bare soil surfaces expose the soil to erosion and moisture loss agents Chowdhury et al., 2016). The use of excessive tillage operations is harmful to the soil and increases the cost of production. Conventional tillage is known to deteriorate soil structure (Sibutis et al., 2009). Low crop production due to moisture stress exacerbates food and nutrition insecurity in sub-Saharan Africa (Das et al., 2015).

Water loss management includes crop management practices and remedial aspects of breeding that enable effective use of limited ASAL water using soil and water conservation techniques. This practice is adopted in many semi-arid environments with low and unreliable rainfall, such as in Eastern Kenya (Johnson et al., 2018). It is necessary to shift from traditional tillage systems to climate smart agricultural interventions. This included, but not limited to water harvesting technologies such as zai pits, ngolo pits, contour furrows, tied ridges, minimum tillage, and the use of mulch for the purpose of protecting soil from degradation, conserving soil moisture, and increasing the water use efficiency for crops. Furthermore, the use of appropriate cropping systems such as intercropping could provide solution to increased productivity and minimize the occurrences of low production in the case of failure of one crop.

Water conservation technologies such as tied ridges, contour furrows and zai pits have been reported to improve soil water retention and consequently increasing water use efficiency (WUE) (Bottinelli et al., 2017; Mati et al., 2017). Through their ability to harvest rain water and store it in the soil, water conservation technologies increase the water holding capacity, infiltration, and reduces the evapotranspiration process from the surface of the soil (Karuku et al. 2019; Busari et al., 2015). Reports by Zougamore et al. (2014) have shown that water conservation technologies have the potential to increase crop yield as a result moisture availability and improved nutrient uptake from the soil. This is due to higher diffusivity and movement of the available nutrients to the root zone, which increases uptake and growth of the crops (Micheni et al., 2014).

Water productivity is a key challenge that needs to be improved by an on- farm water balance (Rockstrom et al., 2003). The use of water conservation technologies coupled with proper cropping system provides effective measures to reduce soil water evaporation, improving the soil moisture retention capacity, making water available for uptake and improvingWUE (Li et al., 2016).

Materials and methods

Experimental sites

Two experiments were conducted concurrently under rain fed conditions at Katumani and Kambi Mawe (KALRO) Kenya Agriculture and Livestock Research Organization Katumani Research stations during the 2022/2023 short rain season. Katumani is located at (1^{o} 35' South and 37^{o} 14' East), at an altitude of 1624 meters above sea level. According to Jaetzold et al. (2006), the centre is classified as agro-climatic zone IV, experiencing a bimodal rainfall pattern. The long rains occurring between March and May (MAM), while the short rains occur from October to December (OND).

The temperature in Katumani ranges between a minimum of 14 ^{0}C and maximum of 27 ^{0}C.

The area's dominant soils were formed from a pre-Cambrian basement system rock primarily composed of quartz felspatic gneiss parent material, which was classified as Ferro-chromic Luvisol in the FAO-UNESCO System (Mbayaki and Karuku, 2021).

Kambi Mawe, on the other hand, is a KALRO Sub-Centre in Makueni County, about 75 kilometers from Katumani, at an elevation of 1150 meters above sea level. The center is located at latitude 01^{o}57'S and longitude 37^{o}40'E. The area experiences a bimodal rainfall pattern, with the long rain (LR) season occurring from March to May and the short rain (SR) season from October to December. The average temperature in the area is 24 ^{o}C and an average annual rainfall of 510 mm. The soil types in Kambi Mawe are Chromic Luvisols, which have low nitrogen (N) and phosphorus (P) levels (Omakwe et al., 2023;Syano et al., 2023).

Experimental deign and treatments

The treatments were spread out in a randomized complete block design (RCBD) in a split plot arrangement and replicated in triplicate. The main plots were water conservation technologies (ngolo pits, contour furrows) and conventional tillage as the control, whereas the cropping systems consisted of sole and intercrop systems of two crop varieties of pearl millet (PM1 and PM3) and green grams (N26 and Biashara). The main plots were separated by 2 m path way while each split-plot was separated by 1m path way. Three seeds were plated per hill but later thinned to one seed after germination to reduce on competition for nutrients, water and light and enhance growth and performance. Under the intercrop systems, a row of green gram was sown between two rows of pearl millet. Green gram varieties (Biashara and N26) and pearl millet varieties (PM1 and PM3), adapted to the ecological conditions of the study areas were used as test crops for this study. Conventional tillage was done using oxen plough to break the hard pan a month before planting.

Agronomic practices on the experimental plots

Primary tillage was done with a hand hoe prior to the start of rains in the 2022/2023 short rain season, primary in both sites. It was followed by construction of the water conservation structures (ngolo pits and contour furrows). The control method was the conventional tillage (farmers practice). The main blocks which comprised of water conservation technologies were allocated randomly within the 2 by 2-meter square area. Contour furrows were prepared by digging furrows of 0.5 meters' depth.

During the construction of ngolo pits, a squares measuring 1.5 m × 1.5 m was demarcated. Soil from the centre of the square was dug using hand hoe. The soil dug from the center was heaped evenly on the sides, leaving a pit, 0.5 m deep at the center (ngolo) as described by Kato *et al.* (2001).

Planting was done by placing seeds in holes 5 cm deep. In the sole crop system, a spacing of 75 cm and 25 cm between rows and within plants, respectively was used for pearl millet while green gram was sown at 60 cm and 30 cm between rows and within plants, respectively. In the intercrop system, pearl millet was sown at 90 cm and 20 cm spacing between rows and within plants, respectively and a row of green gram was sown between rows of pearl millet with a spacing of 30 cm from plant to plant. Three seeds of pearl millet and green gram were planted per hill and later thinned to one plant per hill.

Data collection

Weather data

The weather data comprised of relative humidity, rainfall, maximum and minimum air temperature, solar radiation, sunshine hours, and wind speed at 2 m above ground. All these were derived from the meteorological weather stations based at KALRO-Katumani and Makindu research station in Machakos and Makueni Counties, respectively. Minimum and maximum thermometer, gun ballani, hygrometer and anemometer were used for measuring air temperature, solar radiation, humidity and wind speed, respectively. The weather data were used to compute the crop water use and use efficiency using the seasonal crop evapotranspiration (ET) and crop yield using the soil water balance equation (Equation 1)

$$ET = P + I - D + W_g - R + \Delta S \qquad (1)$$

Where;

ET = Evapotranspiration (mm)

P = Total season precipitation (mm)

I = Soil water drainage (mm)

W_g = Amount of water used by the crop through capillary rise from groundwater (mm)

R = Surface runoff

ΔS = Change of soil water content from planting to harvest in the measured soil depth (mm)

Soil sampling

The initial soil characterization was done by sampling soil from a deepness of 0-30 cm through employment of a soil auger from different plots in a zig-zag manner using an Edelman soil auger. A composite was taken to the laboratory for physical and chemical analysis.

Soil pH

Soil pH was analysed using 1:2.5 ratio soil-in-water (w/v) suspension as described by Okalebo et al. (2002). A conical was filled with 25 millilitres of distilled water and 5 grams of air dried soil sample. The pH of the soil was measured by stirring the suspension and letting it stand for half an hour. Afterwards, the pH meter was calibrated using buffer solutions with pH values of 4 and 7.

Soil texture

Soil texture was ascertained using the hydrometer method, and textural classes was concluded using the USDA textural triangle (Bouyoucos, 1962). The described method was used to calculate soil bulk density (Brown and Wherett, 2014).

Soil organic carbon

The determination of The percentage of soil organic carbon (SOC) was done using the Walkley-Black method (Schumacher, 2002). Ten millilitres of potassium dichromate solution were added to a measuring cylinder along with five grams of air-dried soil. The soil was then stirred gently using a stirring rod. This suspension was then let to settle for thirty minutes before 10 millilitres of concentrated sulfuric acid was then added to the suspension. This was followed by adding 10 ml of ferrous sulphate to the suspension, slowly until the solution turned pale green. Organic carbon was determined using the formulae described by Schumer, 2002) (Equation 2).

$$\%organiccarbon = \frac{[M*(V1-V2)]}{S} * 0.39 * 2.71 \qquad (2)$$

Where;

M is the molarity of ferrous sulphate 9 from blank titration), V1 is the volume of ferrous sulphate needed for the blank, V2 is the volume of ferrous sulphate needed for the soil sample, while S is the weight of the soil sample.

Total nitrogen

Total nitrogen was determined using a micro-Kjeldhal digestion method as described by Keeney and Nelson, 1982). This was done by transferring 0.5 mm of air-dried soil into the digestion tube followed by 2.5 ml of the Kjedhal catalyst. The mixture was heated at 100 0C, for two hours. The mixture was then allowed to cool after which 2ml of hydrogen peroxide was added until a clear and colourless solution was obtained. To find out the total nitrogen, this solution was made up to 75 mL with distilled water.

Total nitrogen was calculated using Equation 3

$$\%\, Total\ nitroegen = \frac{[(a-b)*75}{Weight\ of\ soil\ (g)} * 1000 \qquad (3)$$

Where; a is the nitrogen content of soil sample, b is the nitrogen content of blank, 1000 is the coefficient of conversion from ppp to N to percent N, while 75 ml is the final volume of te digest.

Available phosphorus

The determination of available phosphorus was done using the Olsen method (Elrashidi, 2010). This included adding 0.025 hydrochloric acid and 0.03 ammonium phosphate concentrate to a 100 ml conical flask containing 5g of air-dried soil representative that had been traversed in a 2 mm sieve.The mixture was then put on a mechanical shaker for five minutes. It was then allowed to cool in order to develop change the colour to blue. This was then followed by adding distilled water to make up to 25 ml and allowed to stand for one hour. 0.1, 2.0, 2.4, 3.6, 4.8, and 6.0 mg. The absorbance at 882 nm was measured with a spectrometer and the available P was calculated using the following formula below (Equation 4).

$$Phosphorus = [a - b) * 14\frac{}{s} * moistureconversionfacot$$

(4)

Where; a- is the phosphorus in the soil sample, b is the phosphorus in the blank sample, whereas S is the weight of the soil in grams.

Soil moisture determination

Soil samples were collected randomly from the experimental plots using the soil auger at 0-20, 20-40 and 40-60 cm depths down the soil profile. The collected samples were then thoroughly mixed to get a composite sample. 50 g soil was placed in a pre-weighed khaki bags (W1) and the joint weight of the soil and bag (W2) were recorded. The soil together with the khaki bags were taken to the laboratory at KALRO Katumani oven - drying at 105°C for 24 hours. The oven-dried weight was recorded as (W3) and the difference inn oven dried ad fresh soil samples was calculated to get the amount of soil moisture content.

Soil moisture content was computed gravimetrically using (Equation 5).

$$Gravimetricmoisturecontent(\%) = \frac{W2-W3}{W3-W1} \times 100 \qquad (5)$$

Where: W1 = the weight of empty khaki bag

W2 = weight of the khaki bag + fresh soil

W3 = weight of the khaki bag + oved dried soil sample

The gravimetric soil moisture content was then changed into volumetric proportion by multiplying with bulk density (Equation 6) and converted to volumetric water (mm) by multiplying by soil depth and divided by 10 (Equation 6 and 7).

$$Volumetricmoisture(\%) = Gravimetricwater(\%) \times BulkDensity\left(\frac{g}{cm3}\right)(6)$$

$$Volumetricwater(mm) = \frac{volumetic\% \times SoilDepths(cm)}{10}(7)$$

Determination of water use efficiency

According to Monteith's (1977) description, the crop WUE was calculated using the seasonal crop evapotranspiration (ET) and crop yield. Equation 4 of the soil water balance was used to calculate the seasonal evapotranspiration (Equation 8)

$$ET = P + I - D + W_g - R + \Delta S \qquad (8)$$

Where;

ET = Evapotranspiration (mm)

P = Total season precipitation (mm)

I = Soil water drainage (mm)

W_g = Amount of water used by the crop through capillary rise from groundwater (mm)

R = Surface runoff

ΔS = Change of soil water content from planting to harvest in the measured soil depth (mm)

The variance between input (rainfall, R, and irrigation, I) and output (evapotranspiration, ET, and root zone drainage, D) was deemed to be the same as the change in root zone soil moisture (ΔS). Equation 9 illustrates how soil moisture variation in the root zone (ΔS) was calculated by measuring soil moisture (gravimetrically) at the start and finish of crop growth stages (Equation 6).

$$\Delta S = (R + I) - (ET + D) \qquad (9)$$

Where,

ΔS = Change in soil water storage in the root zone

ET = Evapotranspiration

R = Rainfall

D = Root zone drainage.

Runoff in the study area was assumed to be negligible due to the sandy nature of the soil and the low slope of less than 2.5%. Similarly, drainage below the root zone is determined during the growing season and is therefore considered negligible. (Zhang et al., 2007).

The WUE was then figured from the water use and total biomass yield (Equation 7) (Ahmad et al., 2017; Vanuytrecht et al., 2014).

$$Wateruseefficiency\left(\frac{\frac{Kg}{ha}}{mm}\right) = \frac{Yield\left(\frac{Kg}{ha}\right)}{Cropevapotranspiration(mm)} \quad (10)$$

Statistical analysis

The field data on soil moisture and water use efficiency were subjected to analysis of variance (ANOVA) using GenStat statistical software, 15th Edition (Payne et al., 2005). A two-way ANOVA was carried out to determine the significance levels. Mean separation was performed using Tukey HSD significance level at 5% probability level. Iteratemeasurements were used to analyse soil gravimetric moisture content. Graphs were displayed through application of Excel software.

Results

Soil moisture content

In Kambi Mawe, there was a significant interaction between days after planting × depth, time × water harvesting technologies, cropping systems × depth a between time × water harvesting technologies and depth ($p < 0.001$).

The average soil moisture content in the water harvesting technologies was in the order of ngolo pits > contour furrows > conventional tillage. Soil moisture varied significantly ($p < 0.001$) with days after planting. Soil moisture was higher at planting, compared to soil moisture recorded 30 days, 60 days and at harvest (Table 3).

There was no significant variation of soil moisture among the cropping systems ($p = 0.052$). At all the sampling times, however, the interaction between cropping systems × depth was observed ($p = 0.022$). Plots with sole crops (pearl millet and green grams) had higher soil water content compared to their intercrops irrespective of the variety (Table 3).

With regard to depths, the soil moisture content was significantly ($p < 0.001$) higher at the 40-60 cm depth than in the 20-40 cm and 0-20 cm and varied significantly among the water harvesting technologies and cropping systems.

In Katumani, there were significant interactions between time × water harvesting technologies, time × depth and time × water harvesting technologies × depth ($p < 0.001$). However, the water harvesting technologies did not significantly affect the soil moisture content ($p = 0.120$). Higher moisture of 10.93 cm3 cm-3 was recorded in sole plots of biashara variety under ngolo pits, while the intercrop plots under conventional PM1 pearl millet variety had the lowest soil moisture content of 9.77 mm.

Comparison of soil moisture content with sites showed that higher moisture content was recorded in Kambi Mawe compared to the soil moisture recorded in Katumani. It was also observed that the soil moisture content increased significantly with depth. Higher soil moisture was recorded at 40-60 cm depth compared to soil moisture at 20-40 cm and 0-20 cm

Table 3 shows the interactive effects of *in-situ* water harvesting technologies, cropping systems and depth on soil moisture content (SMC) recorded at different days after emergence (DAE).

Water use efficiency of pearl millet

Highest water uses efficiency (WUE) of pearl millet (9.69 kg ha^{-1} mm^{-1}) was recorded in ngolo pits where PM3 was intercropped with biashara green gram variety, while the lowest value (2.68 kg ha^{-1} mm^{-1}) was recorded in conventional tillage with sole cropping of PM1 in the Kambi Mawe. Similar trends were observed for contour furrows and conventional tillage where the WUE values ranged from 2.17 to 5.34 kg ha^{-1} mm^{-1} and 1.73 kg ha^{-1} mm^{-1} to 5.57 kg ha^{-1} mm^{-1} recorded from PM1 variety to the intercrop between PM3 and biashara green gram variety, respectively. The effect of water harvesting technologies, cropping systems as well as their interactions, were significant (p = 0.048), (p = 0.001), and (p = 0.036) in Kambi Mawe (Table 4). The effect of water harvesting and cropping systems were not significant in influencing the WUE of pearl millet in Katumani.

.

Discussion

Soil moisture content

The volumetric soil moisture content was considerably ($p < 0.001$) higher under water conservation technologies compared to conventional tillage in Kambi Mawe.This can be attributed to increased rainwater storage in the pits and furrows during the growing season. Similar finding has been presented by Zougamore et al. (2014) who reported an increase in soil moisture content under tied ridges to up to 20% in comparison to the conventional tillage practice.This can be ascribed to the high total porosity resulting from the low bulk density caused by soil disturbance caused by the construction of water harvesting structures.

Furthermore, the higher soil moisture stored under ngolo pits compared to conventional tillage may be due to the design of the pit, which allows for the catchment and retaining of more water than relatively flat surfaces in conventional tillage system which had little potential to capture ad store rain water. Wafula et al. (2022) while working in Katumani reported similar findings where ngolo pits recorded a leading soil moisture content in comparison to conventional tillage under the maize-bean intercropping system.

The average soil moisture content for the total growing period at the different depth followed the tendency of ngolo pits > contour furrows > conventional tillage, with highest soil moisture recorded at the lower depths (40-60 cm). This could be attributed to the high uptake by the roots at the upper 0-20 cm depth. This is the depth where the plant roots are active, and therefore, the uptake for water and nutrients is high to support vegetative growth. Esilaba et al. (2017) reported similar findings in a study on maize-cowpea/ maize-dolichos intercrop at Katumani research center. Parvin (2012) also reported that soil moisture content increased with depth.

Water use efficiency of pearl millet

Water use efficiency point out to the ratio of biomass accumulation signified as carbon uptake or grain yield to the amount of water consumed (Niu et al., 2011; Ullah et al., 2019). Higher WUE values recorded in Kambi Mawe compared to Katumani could be attributed high amount of water utilized in Kambi Mawe as a result of the significant effect of the water conservation technologies. Further reasons might be because of the little and insufficient rainfall amount prevailing in Katumanithroughout the entire growing season, which led to stunted growth and eventually low yields. There is a positive correlation between yield and water use efficiency. These findings agree with Hatfield and Dold (2019) who asserted that highest WUE is attained at the highest yields.

Sufficient moisture conditions in the pits could have increased the supply of essential nutrients present in the soil, thereby promoting pearl millet growth.As a result, land cover development increased, which helped reduce soil evaporation losses and improve water use efficiency of pearl millet. Monteith (1994) found that early canopy development allows crops to intercept more radiation, promote root growth, and dispense more water extracted by roots to transpiration, thereby increasing water use efficiency.

In this study, it was observed that the increase in water use efficiency corresponds to the decrease in water use (ETc) of pearl millet. This is in contrast to the findings of Jones (2004), who observed that plants tend to be more efficient in water use when water supply is low.

Conclusion

The outcome from the experiment indicate that soil and water conservation technologies had a significant effect on soil moisture content, crop water use efficiency and yields of pearl millet and green gram. This is due to the fact that the soil and water conservation technologies conserved mores water at beneath the soil profile and kept the soil micro and macro pores intact, maintaining the soil structure, hence creating a conducive environment for the proliferation of the crops. Furthermore, this conditions could have created a friendlier environment for the diffusivity of soil nutrient in the soil, hence promoting faster and quicker uptake by the plant roots.

The water and soil conservation structures act as water reservoirs, to capture and store water for a long period for easy infiltration. This makes the infiltration process easier, which increases the soil's moisture content. When contrasted with contour furrows and conventional tillage, ngolo pits yielded a high up moisture content, higher water use efficiency as well as pearl millet and green gram yields. More rainwater was retained in ngolo pits, where it was at the lowest point relative to surface flow and had more span to seep into the soil. The increase in grain yield due to increased water storage capacity from available rainfall was the primary cause for the increment of pearl millet’s water use and water use efficiency under ngolo pits. The findings also demonstrated the importance of seasonal variations for pearl millet and green grams. This was primarily ascribed to the rainfall's distribution, intensity, and quantity.

Conversely, intercropping increased the number of plants, which increased competition for nutrients, moisture, and light energy in the soil. The soil moisture content was over extracted as a result. The amount of moisture in the soil was not significantly affected by the various varieties.

REFERENCES

Abubaker, B. M. A., En, Y. S., Cheng, S. G., and Alhadi, M. (2014). Impact of different water harvesting technologies on soil moisture content and yield components of sorghum. *Pak. J. Agri. Sci*, *51*(779.788).

Adeboye, O. B., Schultz, B., Adekalu, K. O., & Prasad, K. (2016). Impact of water stress on radiation interception and radiation use efficiency of soybeans (Glycine max L. Merr.) in Nigeria. *Brazilian Journal of Science and Technology*, *3*(1), 1-21.

Ahmad, L., Parvaze, S., Parvaze, S., and Kanth, R. H. (2017). Crop water requirement of saffron (Crocus sativus) in Kashmir valley. *Journal of Agrometeorology*, *19*(4), 380-381.

Angadi, S., & Patil, B. L. (2018). Economics of cost of cultivation of Greengram in Gadag district of Karnataka. *Journal of Pharmacognosy and Phytochemistry*, *7*(3), 1206-1210.

Ayanlade, A., Radeny, M., Morton, J. F., and Muchaba, T. (2018). Rainfall variability and drought characteristics in two agro-climatic zones: An assessment of climate change challenges in Africa. *Science of the Total Environment*, *630*, 728-737.

BM A, A., Shuang-En, Y., Guang-Cheng, S., & Alhadi, M. (2014). Impact of different water harvesting techniques on soil moisture content and yield components of sorghum. *Pakistan Journal of Agricultural Sciences*, *51*(4).

Bramley, H., Turner, N. C., & Siddique, K. H. (2013). Water use efficiency. In *Genomics and breeding for climate-resilient crops* (pp. 225-268). Springer, Berlin, Heidelberg.Critchley, W., Siegert, K., Chapman, C., and Finket, M. (2013). Water harvesting: A manual for the design and construction of water harvesting schemes for plant production. Scientific Publishers.

Eswaran, R., & Senthilkumar, N. (2015). Correlation and path analysis in green gram (Vigna radiata) (L.) Wilczek] for drought stress. Plant Archives, 15(1), 247-249.

Gandah, M., Bouma, J., Brouwer, J., Hiernaux, P., and Van Duivenbooden, N. (2003). Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, West Africa. *Agriculture, ecosystems & environment*, *94*(3), 311-319.

Gebreegziabher, T., Nyssen, J., Govaerts, B., Getnet, F., Behailu, M., Haile, M., & Deckers, J. (2009). Contour furrows for in situ soil and water conservation, Tigray, Northern Ethiopia. *Soil and Tillage Research*, *103*(2), 257-264.

Gebru, H. (2015). A review on the comparative advantages of intercropping to mono-cropping system. *Journal of Biology, Agriculture and Healthcare*, *5*(9), 1-13.

Gebru, H. (2015). A review on the comparative advantages of intercropping to mono-cropping system. *Journal of Biology, Agriculture and Healthcare*, *5*(9), 1-13.

Hassan, Z. M., Sebola, N. A., and Mabelebele, M. (2021). The nutritional use of millet grain for food and feed: a review. *Agriculture & Food Security*, *10*(1), 1-14.

Hatfield, J. L., & Dold, C. (2019). Water-use efficiency: advances and challenges in a changing climate. *Frontiers in plant science*, *10*, 103.

Hatibu, N., &Mahoo, H. (1999). Rainwater harvesting technologies for agricultural production: A case for Dodoma, Tanzania. *Conservation tillage with animal traction, 161.*

Ijoyah, M. O. (2012). Review of intercropping research: Studies on cereal-vegetable based cropping system. *Scientific Journal of Crop Science*, *1*(3), 55-62.

Itefa, D. (2016). General characteristics and genetic improvement status of Mung bean (Vigna radiata L.) in Ethiopia: Review article. International Journal of Agriculture Innovations and Research, 5(2), 2319-1473.

Johnson, Y. K., Ayuke, F. O., Kinama, J. M., &Sijali, I. V. (2018). Effects of tillage practices on water use efficiency and yield of different drought tolerant common bean varieties in Machakos county, Eastern Kenya. *American Academic Scientific Research Journal for Engineering, Technology, and Sciences*, *40*(1), 217-234.

Jones, H. (2004). What is water use efficiency. *Water use efficiency in plant biology*, 27-41.

Jukanti, A. K., Gowda, C. L., Rai, K. N., Manga, V. K., & Bhatt, R. K. (2016). Crops that feed the world 11. Pearl Millet (Pennisetum glaucum L.): an important source of food security, nutrition and health in the arid and semi-arid tropics. *Food Security*, *8*(2), 307-329.

Jukanti, A. K., Gowda, C. L., Rai, K. N., Manga, V. K., & Bhatt, R. K. (2016). Crops that feed the world 11. Pearl Millet (Pennisetum glaucum L.): an important source of food security, nutrition and health in the arid and semi-arid tropics. *Food Security*, *8*, 307-329.

Karimi, R., Nair, R. M., Ledesma, D., Mutisya, D. L., and Muthoni, L. (2019). Performance and participatory evaluation of green gram genotypes in the semi-arid environments of Eastern Kenya. East African Agricultural and Forestry Journal, 83(2), 119-136.

Karuma, A. N., Mtakwa, P. W., Amuri, N., Gachene, C. K. K., Gicheru, P., & Karuma, A. (2012). Effect of different tillage methods on soil moisture dynamics in -bean cropping systems in semi-arid Mwala district, Kenya. In *Third RUFORUM Biennial Meeting* (pp. 24-28).

Kato, E., Ringler, C., Yesuf, M., and Bryan, E. (2011). Soil and water conservation technologies: a buffer against production risk in the face of climate change? Insights from the Nile basin in Ethiopia. *Agricultural Economics*, *42*(5), 593-604.

Kavya, N. (2014). Nutritional and therapeutic of uses of Mudgavigna radiata: A potential interventional dietary component. Int. J. Res. Ayurveda Pharm, 5(2), pp.238-241

Kinama, J. M., & Pierre, H. M. J. (2018). A review on advantage of cereals-legumes intercropping system: Case of promiscuous soybeans varieties and maize. *International Journal of Agronomy and Agricultural Research*, *12*(6), 155-165.

Kinama, J. M., Stigter, C. J., Ong, C. K., & Gichuki, F. N. (2005). Evaporation from soils below sparse crops in contour hedgerow agroforestry in semi-arid Kenya. *Agricultural and forest meteorology*, *130*(3-4), 149-162.

Kinama, J. M., Stigter, C. J., Ong, C. K., Ng'ang'a, J. K., & Gichuki, F. N. (2007). Contour hedgerows and grass strips in erosion and runoff control on sloping land in semi-arid Kenya. *Arid land research and management*, *21*(1), 1-19.

Kinama, J., Stigter, C., Ong, C., Nganga, J., & Gichuki, F. (2007). Alley cropping (contour hedgerow intercropping) maize or cowpea/senna for increased dry matter production in the semi-arid areas of eastern Kenya. *Proceedings of African Crop Science Society (ACSS) in Melkia–Egypt.*

Kisaka, M.O., Mucheru-Muna, M., Ngetich, F.K., Mugwe, J.N., Mugendi, D. and Mairura, F., (2015). Rainfall variability, drought characterization, and efficacy of rainfall data reconstruction: case of Eastern Kenya. Advances in Meteorology, 2015

Kiteme B, Ehrensperger A. 2015. The ngolo farming technology. In: Ehrensperger A, Ott C, Wiesmann U, editors. Eastern and Southern Africa Partnership Programme: Highlights from 15 Years of Joint Action for Sustainable Development. Bern, Switzerland: Centre for Development and Environment (CDE), University of Bern, with Bern Open Publishing (BOP), pp. 23–26. http://doi.org/10.7892/boris.72023.

Kogo, B. K., Kumar, L., & Koech, R. (2021). Climate change and variability in Kenya: a review of impacts on agriculture and food security. Environment, Development and Sustainability, 23(1), 23-43.

Kugedera, A. T., Kokerai, L. K., & Chimbwanda, F. (2018). Effects of insitu rainwater harvesting and integrated nutrient management options on Sorghum production. *GSJ*, *6*(12).

Kumar, A., & Kumar, P. (2018). Performance of advance pearl millet hybrids and mungbean under sole cropping and intercropping systems under semi-arid environment. *Journal of Pharmacognosy and Phytochemistry*, *7*(2), 1671-1675.

Kumar, A., & Kumar, P. (2018). Performance of advance pearl millet hybrids and mungbean under sole cropping and intercropping systems under semi-arid environment. *Journal of Pharmacognosy and Phytochemistry*, *7*(2), 1671-1675.

Kurothe, R. S., Kumar, G., Singh, R., Singh, H. B., Tiwari, S. P., Vishwakarma, A. K., ... & Pande, V. C. (2014). Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. *Soil and Tillage Research*, *140*, 126-134.

Macauley, H., &Ramadjita, T. (2015). Cereal crops: Rice, maize, millet, sorghum, wheat.

Machocho, A. K., Rugumamu, C. P., Birgen, J. K., Amuka, O., & Asiimwe, E. (2012). The status of green gram production, pest and disease management in parts of Lake Victoria basin. In *Ethnobotany and Health. Proceedings of the Cluster Workshop, Entebbe, Uganda, 4-7 September 2010* (pp. 81-90). Inter-University Council for East Africa Lake Victoria Research Initiative.

Malley, Z. J. U., Kayombo, B. Willcocks, T. J. and P. W. Mtakwa, (2004). Ngoro: an indigenous, sustainable and profitable soil, water and nutrient conservation system in Tanzania for sloping land. Soil Tillage Res., 77, 47 – 58.

Manyatsi, A. M., Mhazo, N., Mkhatshwa, M., and Masarirambi, M. T. (2011). The effect of different in-situ water conservation tillage methods on growth and development of Taro (Colocasia esculenta L.). Asian Journal of Agricultural Sciences, 3(1), 11-18.

.Mehta, R., & Pandey, V. (2016). Crop water requirement (ETc) of different crops of middle Gujarat. *Journal of Agrometeorology*, *18*(1), 83-87.

Miriti, J. M., Kironchi, G., Esilaba, A. O., Heng, L. K., Gachene, C. K. K., and Mwangi, D. M. (2012). Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. Agricultural Water Management, 115, 148-155.

Monteith, J. L. (1994). Validity of the correlation between intercepted radiation and biomass. *Agricultural and Forest meteorology*, *68*(3-4), 213-220.

Mudatenguha, F., Anena, J., Kiptum, C. K., & Mashingaidze, A. B. (2014). In situ rain water harvesting techniques increase maize growth and grain yield in a semi-arid agro-ecology of Nyagatare, Rwanda. *Int. J. Agric. Biol*, *16*, 996-1000.

Mugo, J. W., Kariuki, P. C., & Musembi, D. K. (2016). Identification of suitable land for green gram production using GIS based analytical hierarchy process in Kitui County, Kenya.

Mutiso, P. M. (2018). Effect of fertilizer micro-dosing and in situ moisture conservation on yield and resource use efficiency of pearl millet in Makueni County-Kenya (Doctoral dissertation, University of Nairobi).

Mutua, L. N., Omuterema, S., and Gweyi, J. O. (2016). Evaluation of the nature of drought experienced in Makueni county, Kenya. *Research on Humanities and Social Sciences*, *6*(16).

Mweu, B. M. (2017). Adaptability of pearl millet (Pennisetum glaucum (L.) R. Br) varieties in the semi-arid Kitui County of Kenya (Doctoral dissertation).

Ndiku, M. H., Jara, E., &Sabaté, J. (2014). Formative research on acceptability of pearl millet in rural eastern Kenya– A pilot study. *Sustainable Agriculture Research*, *3*(526-2016-37908).

Nema, A. K., Maruthi Sankar, G. R., & Chauhan, S. P. (2008). Selection of superior tillage and fertilizer practices based on rainfall and soil moisture effects on pearl millet yield under semiarid inceptisols. *Journal of Irrigation and Drainage Engineering*, *134*(3), 361-371.

Newman, Y., Jennings, E. D., Vendramini, J., & Blount, A. (2010). Pearl Millet (Pennisetum glaucum): Overview and Management: SS-AGR-337/AG347, 9/2010. *EDIS*, *2010*(7).

Niu, S., Xing, X., Zhang, Z. H. E., Xia, J., Zhou, X., Song, B., ... & Wan, S. (2011). Water□use efficiency in response to climate change: from leaf to ecosystem in a temperate steppe. *Global Change Biology*, *17*(2), 1073-1082.

Obilana, A. B. (2003). Overview: importance of millets in Africa. *World (all cultivated millet species)*, *38*, 28.

Paslawar, A. N., &Deotalu, A. S. (2015). Impact of soil moisture conservation practices and nutrient management under high density planting system of cotton. *The International Journal of Engineering and Science*, *4*(9), 34-36.

Passioura, J. (2006). Increasing crop productivity when water is scarce—from breeding to field management. *Agricultural water management*, *80*(1-3), 176-196.

Passioura, J. B., and Angus, J. F. (2010). Improving productivity of crops in water-limited environments. In Advances in agronomy (Vol. 106, pp. 37-75). Academic Press.

Rani, S., Goyat, R., & Soni, J. K. (2017). Pearl millet [Pennisetum glaucum L.] intercropping with pulses step towards increasing farmer's income under rainfed farming: A review. *The Pharma Innovation Journal*, *6*(10), 385-390.

Rankoana, S. A. (2020). Food security under unreliable rainfall: the case study of a rural community in Limpopo Province, South Africa. *Journal of Water and Climate Change*, *11*(3), 677-684.

Recha, J., Kinyangi, J., and Omondi, H. (2013). Climate related risk and opportunities for agricultural adaption and mitigation in semiarid eastern Kenya. Climate change.

Rockström, J., Barron, J., & Fox, P. (2003). Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. *Water productivity in agriculture: Limits and opportunities for improvement*, 145-162.

Rockström, J., Barron, J., and Fox, P. (2003). Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. Water productivity in agriculture: Limits and opportunities for improvement, 85199(669), 8.

Saleh, A. S., Zhang, Q., Chen, J., & Shen, Q. (2013). Millet grains: nutritional quality, processing, and potential health benefits. *Comprehensive reviews in food science and food safety*, *12*(3), 281-295.

Sivakumar, M. V. K., & Salaam, S. A. (1999). Effect of year and fertilizer on water-use efficiency of pearl millet (Pennisetum glaucum) in Niger. *The Journal of Agricultural Science*, *132*(2), 139-148.

Vanuytrecht, E., Raes, D., Steduto, P., Hsiao, T. C., Fereres, E., Heng, L. K., ... & Moreno, P. M. (2014). AquaCrop: FAO's crop water productivity and yield response model. *Environmental Modelling & Software*, *62*, 351-360.

Wafula, K. M. (2022). Effect of in-situ Water Harvesting Technologies and Fertilizer Application on Nutrient Uptake, Use Efficiency, and Yield of Maize and Beans in Katumani, Machakos County, Kenya (Doctoral dissertation, University of Nairobi).

.

Webber, H. A., Madramootoo, C. A., Bourgault, M., Horst, M. G., Stulina, G., & Smith, D. L. (2006). Water use efficiency of common bean and green gram grown using alternate furrow and deficit irrigation. *Agricultural Water Management*, *86*(3), 259-268.

Table 1

Physical and chemical properties of the soil in the study sites

Soil properties	Parameters	Units	Kambi Mawe	Katumani
Physical	Bulk density	g/cm3	1.35	1.46
	Ksat	cm/hr	1.34	1.19
	Sand	%	73	69
	Silt	%	8.0	7.0
	Clay	%	19	24
	Textural class		SCL	SCL
Chemical	pH (H_2O)	v/v (H_2O)	6.4	6.8
	Organic carbon (OC)	%	1.3	1.4
	Total Nitrogen	%	0.15	0.23
	Phosphorus (P)	ppm	23.9	32.1
	Potassium (K)	Cmol/kg	1.9	1.9
	Calcium (Ca)	Cmol/kg	5.57	6.34
	Magnesium	Cmol/kg	1.78	1.23
	Zinc (Zn) (ppm)	ppm	13.5	14.5
	Iron (Fe)	ppm	63.8	56.3
	Copper (Cu)	ppm	15.9	16.5

Table 2

Monthly climatic data during crop growing seasons

Site	Months	Rainfall	Temperature		RH	WS	ET_o
		(mm)	Tmax	Tmin	(%)	m/s	mm/day
Kambi Mawe	November	11.2	29.0	19.0	78.7	74.3	102.0
	December	91.9	29.3	19.1	79.9	77.2	108.6
	January	11.2	31.0	19.5	72.6	86.3	148.7
	February	139.3	29.0	19.0	78.7	120.1	102.0
Katumani	November	54.1	25.7	15.9	83.2	73.1	100.4
	December	25.1	24.0	14.4	84.5	70.8	163.1
	January	23.5	25.2	16.5	80.2	89.6	199.5
	February	0	27.9	13.8	68.0	78.9	222.5

Legend: Tmax- maximum temperature; Tmin- minimum temperature; RH- relative humidity; WS- wind speed

Table 3

Interactive effects of in-situ water harvesting technologies, cropping systems on soil moisture content (mm) at different sampling times during the 2022/23 cropping season at Kambi Mawe and Katumani experimental sites.

	Kambi Mawe				Katumani			
Treatments	Planting	30days	60days	Harvest	Planting	30days	60days	Harvest
Water harvesting technologies (T)								
Ngolo pits	17.91	15.91	14.88	10.51	14.17	12.40	10.97	10.41
Contour furrows	15.39	15.01	13.13	10.12	12.32	11.78	10.06	9.49
Conventional tillage	13.29	13.21	12.03	10.29	12.14	10.58	9.17	9.22
Cropping systems (CS)								
PM1	15.87	14.63	14.55	10.89	12.27	12.65	9.77	9.49
PMI + Biashara	16.68	14.71	13.83	10.49	12.09	12.19	10.72	9.41
PM1 + N26	15.49	14.39	14.91	10.82	12.83	11.81	10.39	9.48
PM3	15.98	14.34	13.34	10.91	12.52	11.84	10.34	9.01
PM3 + Biashara	16.34	14.75	13.05	10.39	11.93	11.71	10.40	9.32
PM3 + N26	15.64	15.04	13.82	10.44	11.91	11.06	10.39	9.00
Biashara	16.17	14.53	14.78	10.21	11.33	11.82	10.93	9.10
N26	15.83	14.86	13.43	10.82	11.72	11.24	10.49	9.48
Depths								
0-20 cm	14.05	12.39	13.74	16.48	14.18	15.38	22.51	10.36
20-40 cm	16.28	15.61	13.57	21.54	16.46	15.31	19.34	15.08
40-60 cm	18.75	16.32	14.59	22.84	18.67	14.68	21.11	18.01
Significance levels								
	Time	T	CS	Depth	time× T	T × CS × Depth		

Kambi Mawe	<.001	0.014	0.052	0.001	0.022	0.012
Katumani	<.001	0.120	0.533	0.009	0.043	0.017

Legend: T- water harvesting techniques, CS- cropping systems

Table 4

Effects of water harvesting technologies and cropping systems on water use efficiency of pearl millet in Kambi Mawe and Katumani during 2022/2023 cropping season

		Kambi Mawe	Katumani
Technologies	Cropping System	WUE (kgha^{-1} mm^{-1})	WUE (kgha^{-1} mm^{-1})
Ngolo	PM1	2.68^{c}	1.28^{a}
	PM3	6.38^{b}	2.35^{a}
	PM1+N26	7.29^{ab}	1.47^{a}
	PM1+Biashara	7.89^{b}	3.34^{a}
	PM3+N26	7.01^{b}	2.03^{a}
	PM3+Biashara	9.69^{a}	1.77^{a}
Contour furrows	PM1	2.87^{c}	1.57^{a}
	PM3	4.78^{b}	1.08^{a}
	PM1+N26	6.04^{ab}	1.93^{a}
	PM1+Biashara	6.41^{ab}	1.52^{a}
	PM3+N26	4.30^{b}	1.43^{a}
	PM3+Biashara	1.83^{d}	1.27^{a}
Conventional tillage	PM1	1.73^{d}	0.72^{a}
	PM3	1.69^{d}	0.76^{a}
	PM1+N26	4.47^{c}	1.08^{a}
	PM1+Biashara	1.66^{d}	0.88^{a}
	PM3+N26	4.97^{b}	1.47^{a}
	PM3+Biashara	5.57^{ab}	1.38^{a}
Summary of p-values			
Water harvesting technologies		0.048	0.900
Cropping systems		0.001	0.768

Interaction (T × CS)	0.036	0.639

Legend: T-water harvesting technologies, CS-cropping systems

Figure 1

Effect of water conservation technologies and cropping systems on WUE of pearl millet grain yield.