



EFFECTS OF RAINWATER HARVESTING PRACTICES ON BIOMASS YIELD AND MORPHOMETRIC TRAITS OF SORGHUM (*Sorghum bicolor* L. Moench) IN SEMI-ARID KITUI COUNTY, KENYA †

[EFECTOS DE LAS PRÁCTICAS DE RECOLECCIÓN DE AGUA DE LLUVIA SOBRE EL RENDIMIENTO DE BIOMASA Y LOS RASGOS MORFOMÉTRICOS DEL SORGO (*Sorghum bicolor* L. Moench) EN EL CONDADO SEMIÁRIDO DE KITUI, KENIA]

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SUMMARY

Background: Sorghum is an important source of fodder in the semi-arid areas of Kenya. However, its biomass yield has remained low due to the low soil moisture content which is associated with low rainfall. **Objective:** To evaluate the synergistic effects of combining rainwater harvesting practices on biomass yield and the morphometric traits of sorghum in semi-arid Kitui County. **Methodology:** The study was conducted in a randomized complete block design under rainfed conditions between March and August 2021 at the Research Farm of South Eastern Kenya University. It had twelve treatments, including three farming systems (conventional flat planting, ridge and furrow, and zai pits) with three soil mulching types (transparent plastic film mulch, black plastic film mulch, and grass mulch). The farming systems without mulching were used as control treatments. Data were subjected to analysis of variance and means were separated using Fisher's protected Least Significant Difference test at 0.05 %. **Results:** The zai pits with black plastic film mulch and flat planting with grass mulch had the highest and lowest moisture content of 68.65% and 52.5% respectively compared to flat planting. The highest biomass yield was observed in ridge-furrow with black plastic film mulch (3283.33kg ha⁻¹) and ridge-furrow with transparent plastic film mulch (3266.03) and was not significantly different. The lowest biomass yield was recorded in conventional flat planting and zai pits and was not significantly different. In all treatments, there was a significant increase ($p \leq 0.05$) in morphometric traits. **Implications:** The farming system and the type of soil mulching determined the increase of soil moisture content, biomass yield, and morphometric traits. **Conclusion:** Combining ridge-furrow and black plastic mulch is recommended to improve the biomass yield of sorghum in semi-arid Kitui County, and other areas with similar agroecological conditions. **Key words:** Drylands; cereals; water stress; climate change.

RESUMEN

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Antecedentes: El sorgo es una fuente importante de forraje en las zonas semiáridas de Kenia. Sin embargo, su rendimiento de biomasa se ha mantenido bajo debido al bajo contenido de humedad del suelo asociado con la escasez de precipitaciones. **Objetivo:** Evaluar los efectos sinérgicos de la combinación de prácticas de recolección de agua de lluvia sobre el rendimiento de biomasa y las características morfométricas del sorgo en el condado semiárido de Kitui. **Metodología:** El estudio se realizó en un diseño de bloques completos al azar en condiciones de temporal entre marzo y agosto de 2021 en la Granja de Investigación de la Universidad del Sudeste de Kenia. El estudio incluyó doce tratamientos, incluidos tres sistemas agrícolas (plantación plana convencional, camellones y surcos, y hoyos zai) con tres tipos de acolchado del suelo (mantillo de película plástica transparente, mantillo de película plástica negra y mantillo de pasto). Los sistemas de cultivo sin mantillo se utilizaron como tratamientos de control. Los datos se sometieron a análisis de varianza y las medias se separaron utilizando la prueba de diferencia mínima significativa protegida de Fisher al 0,05 %. **Resultados:** Los pozos zai con mantillo de película plástica negra y la plantación plana con mantillo de pasto tuvieron el contenido de humedad más alto y más bajo de 68.65% y 52.5% respectivamente en comparación con la plantación plana. El mayor rendimiento de biomasa se observó en surco-surco con mantillo de película plástica negra (3283.33 kg ha⁻¹) y surco-surco con mantillo de película plástica transparente (3266.03) y no fueron significativamente diferentes. El rendimiento de biomasa más bajo se registró en las plantaciones planas convencionales y en los pozos zai y no fueron significativamente diferentes. En todos los tratamientos hubo un aumento significativo ($p \leq 0.05$) en los rasgos morfométricos. **Implicaciones:** El sistema de cultivo y el tipo de cobertura del suelo determinaron el aumento del contenido de humedad del suelo, el rendimiento de biomasa y los rasgos morfométricos. **Conclusión:** se recomienda combinar caballones-surcos y mantillo plástico negro para mejorar el rendimiento de biomasa de sorgo en el condado semiárido de Kitui y otras áreas con condiciones agroecológicas similares. **Palabras clave:** Tierras Áridas; cereales; estrés hídrico; cambio climático.

INTRODUCTION

Sub-Saharan Africa is faced with the tremendous challenge of producing food and fodder to match the ever-increasing demand (Houkonnou *et al.*, 2012; Jayne and Rashid, 2013). An enormous human and livestock population increase is projected to occur, and this is likely to exacerbate the already existing problem of land shortages. An increase in the human population is expected to create competition for land and create scarcity, particularly in areas where crops are integrated with livestock farming (Kindu *et al.*, 2014; Mueller and Binder 2015). This is already experienced in Kenya and has detrimental effects on food and fodder production, especially in arid and semi-arid areas (GOK, 2015). The scarcity of animal feeds has prompted farmers to feed livestock with crop residues in these fragile agroecosystems, as grazing fields are now being converted to cropland (Kagwiria *et al.*, 2019).

Sorghum is one of Kenya's most important cereal crops grown in semi-arid areas and contributes immensely to food and fodder production (Jacob *et al.*, 2013; Muui *et al.*, 2019). According to Muui *et al.* (2013), sorghum is grown mainly in drought-prone marginal agricultural areas of Eastern, Nyanza, and coast provinces of Kenya. Though sorghum growing has the potential to provide food security and animal feed, people prefer planting maize, which is less adaptable to dry land conditions, and this contributes significantly to continuous food insecurity in the country (Dicko *et al.*, 2006; Orr *et al.*, 2016). Despite its tolerance to harsh environmental conditions, sorghum

production in Kenya has been considerably low, mainly due to low rainfall (Kagwiria *et al.*, 2019). This is aggravated by the fact that a significant amount of rainwater is lost through evaporation. Sorghum production is constrained by abiotic and biotic factors such as low soil fertility, water stress, pests and diseases, weeds, and extreme temperatures, which attenuate its productivity and contribute to food insecurity (Strange and Scott, 2005; Gregory *et al.*, 2005; Knox *et al.*, 2012). Other sorghum production constraints include waterlogging, runoff, and soil erosion, which significantly reduce its yields (Murty *et al.*, 2007).

Kinama *et al.* (2005) working in semi-arid Kenya revealed that 50% of the total rainfall is lost through evaporation. Maximizing rainwater harvesting, reducing the amount of runoff and its subsequent soil erosion, has shown significant improvement in crop yield (Kahinda *et al.*, 2007; Motsi *et al.*, 2004; Musiyiwa *et al.*, 2017; Rockström *et al.*, 2009). Past studies have shown a significant increase in soil moisture content and, subsequently, high crop yields through rainwater harvesting practices in semi-arid areas. The commonly used water harvesting and conservation practices in semi-arid areas include organic mulching, pitting, ridging and furrowing, and terracing (Mupangwa *et al.*, 2006; Musiyiwa *et al.*, 2017). These water harvesting practices increase the infiltration and storage of soil water and decrease water loss through surface evaporation, thereby making more water available to the crops (Kumar and Rana, 2007; Paslawar and Deotalu, 2015). Reducing the runoff through increased infiltration and water storage in the soil profile

leads to a delay in the occurrence of severe water stress, which helps to buffer the crop against detrimental effects caused by water deficits during drought periods (Nyamadzawo *et al.*, 2013).

Though the aforementioned techniques have shown the potential of increasing biomass yields, they have setbacks in maintaining soil moisture for efficient crop growth, for instance, organic mulch is decomposed by termites, thus reducing its ability to conserve soil moisture. Besides, temperatures are usually high in arid and semi-arid areas and this increases the evaporation rate, resulting in low soil moisture content. Plastic film mulching practices have shown a significant effect on increasing soil moisture (Mo *et al.*, 2018). This study, therefore, was designed to evaluate the synergistic effects of mulching materials and rainwater harvesting practices on biomass and morphometric traits of sorghum in Kitui County, Kenya.

MATERIALS AND METHODS

Description of the site

The research was done in Kitui County, Kenya, located approximately 170 km east of Nairobi. The coordinates of the study site were 1° 19' 15" S, 37° 45' 43" E (Figure 1). The area is found in the Agro-Ecological Zone Lower Midland (AEZ LM4) of Kitui County (Jaetzold and Schmidt, 1983). The county receives a bimodal rainfall with an annual range of 250 mm and 1050 mm (County Government of Kitui, 2013, 2018). It has an annual mean minimum temperature range of 22-28°C, and an annual mean maximum temperature range of 28 and 32°C (ROK, 2010). The county is characterized by high evaporation rates and a profound amount of surface flows (Munyao *et al.*, 2004; Muthomi *et al.*, 2015). Acrisols, luvisols, and ferralsols are the most common soil types in Kitui County (Jaetzold 1983). The soils are well-drained and moderately deep (Jaetzold and Schmidt 1983). The majority of the residents (87%) in this county depend on agriculture for their livelihoods (County Government of Kitui, 2018).

Mean monthly rainfall distribution and air temperature during the growing season

The sorghum was planted in March before the onset of the long rain season which usually begins in March and ends in May. The season was characterized by relatively warm temperatures and higher rainfall. The month of April had a higher amount of rainfall (mean 94.92 mm) compared

with the other months. During the growing season, May recorded the lowest monthly mean rainfall (26.37 mm) and air temperature (23.33 °C) compared with the other months (Fig.2).

Treatments and experimental design

A field experiment was carried out in a Randomized Complete Block Design (RCBD) with twelve treatments; which included three farming systems (FP: conventional flat planting, RF: ridge and furrow, ZP: Zai pits), three types of soil mulching (TPM: transparent plastic film mulch, BPM: black plastic film mulch, and GM: grass mulch), and three control treatments: farming practices without mulching treatment. The tested treatments included conventional flat planting + transparent plastic film mulch (T1), conventional flat planting + black plastic film mulch (T2), conventional flat planting + grass mulch (T3), ridge-furrow + transparent plastic mulch (T4), ridge-furrow + black plastic film mulch (T5), ridge-furrow + grass mulch (T6), zai pit + transparent plastic film mulch (T7), zai pit + black mulch plastic (T8), zai pit + grass mulch (T9), conventional flat planting with no mulching (FP), ridging and furrow with no mulching (RF), and zai pit with no mulching (ZP). The treatments were replicated three times, resulting in thirty-six (36) plots, and each plot area measured 5m x 5 m. There were three blocks, each measuring 18 m x 18 m, separated by a distance of 3 m. Each block had twelve plots, which were surrounded by a furrow to control surface run-on.

Before planting, the experimental site was ploughed using a disc plough and levelled using handheld hoes. This followed the manual application of farmyard manure at a rate of 30 t ha⁻¹. The edges of plastic mulches (0.008 mm thick and 120 cm wide) were carefully covered with soil to prevent them from being blown by strong winds. The sundried grass mulch was applied at a rate of 5 t ha⁻¹. Nine zai pits measuring 0.6m in width, 0.6m in length, and 0.6m in depth were prepared in alternate rows and spaced at 0.6–0.8 m to reduce the runoff and increase water infiltration into the soil. In all treatments, sorghum seeds of the Garden variety were planted at a rate of 7 kg ha⁻¹ and a depth of 2 - 4 cm. Four seeds were planted per hill at a spacing of 40cm by 30cm inter- and intra-row, respectively, and later thinned to two seedlings per hill one and a half weeks after germination. Weeds were manually controlled throughout the season, there were no incidences of diseases or pests except birds, which were controlled by scaring.

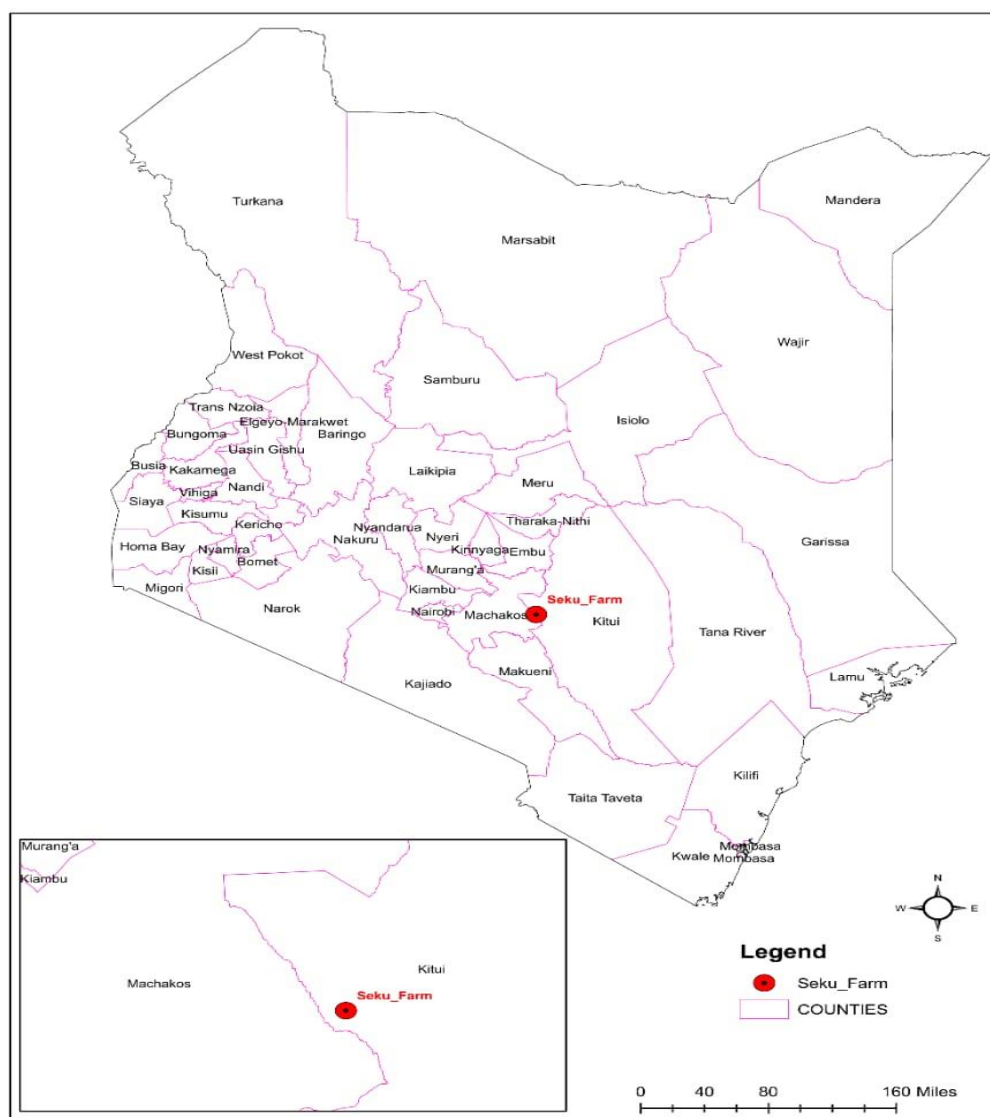


Figure 1. Study site in Kitui County, Kenya,

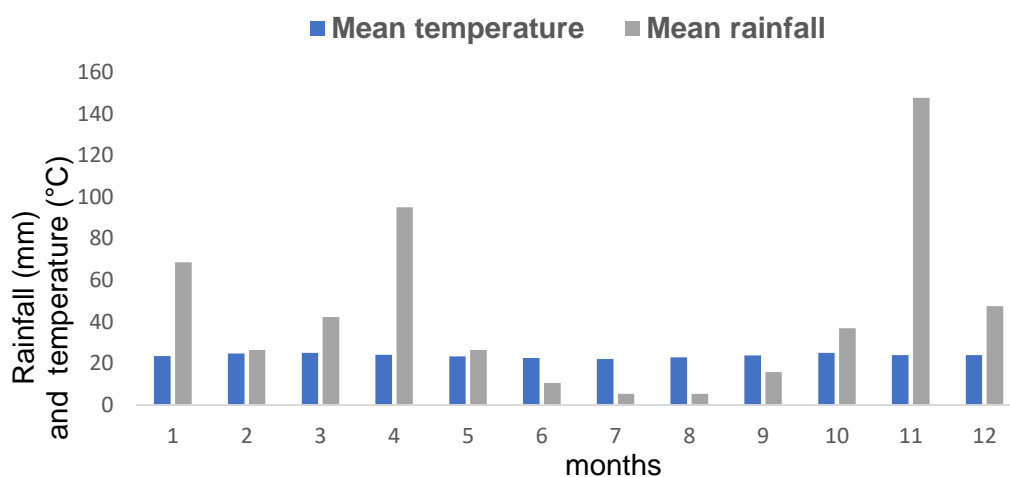


Figure 2. Rainfall and temperature during the sorghum growing period in 2021 at South Eastern Kenya University, Kenya.

Sampling and Measurement

Soil moisture content (%) determination:

In flat and ridge-furrow farming systems, the soil samples were collected near the root zone of plants in four middle rows at a depth of 0.3m and an interval of 2 m weekly. Similarly, in zai pits, the samples were taken near the root zone in the middle row of plants at a depth of 0.3 m and an interval of 0.3 m. The moisture content of soil samples was determined gravimetrically. The soil samples were put in plastic bags, wet weight taken, and oven drying to a stable weight at 105°C, according to Okalebo *et al.* (2002). The percentage moisture content (%) was computed as follows:

Moisture content =

$$\frac{\text{Wet weight (g)} - \text{Oven dry weight (g)}}{\text{Oven dry weight (g)}} \dots\dots\dots (1)$$

Leaf area, plant height, panicle length, number of tillers, and Above-ground biomass

In each plot, ten plants were sampled randomly, at the fifth leaf, during the booting and panicle initiation stages, to measure leaf area, which was calculated by multiplying the length of the leaf by its width and further multiplied by 0.75 according to Birch *et al.* (1998). The plant height was measured from the soil surface to the tip of the sorghum plant once per week from the third week after germination, using a tape measure. The panicle length was measured from the bottom to the top using a tape measure, while the number of tillers in each plot was determined physically by counting. At physiological maturity, six plants in each of the four lines in a plot (equal to 6m²) were sampled and harvested. The harvested panicles were threshed, and grains were put in plastic paper together with their above-ground biomass (stovers and threshed panicles) and later oven-dried at 65° C for 72 hours until there was no further weight loss and were expressed in kg ha⁻¹.

Statistical analysis

The collected data was subjected to Analysis of Variance (ANOVA) using SAS version (9.4 Institute Inc., Cary, NC, USA). Differences between the treatments were considered significant at $p \leq 0.05$, and the means were separated using Fisher's protected Least Significant Difference test (LSD_{0.05}).

RESULTS

The effects of combined *in situ* water harvesting technologies on moisture content, above-ground biomass yield, and leaf area

Mulching materials had a significant effect on increasing soil moisture content ($P < 0.001$, Table 1). The overall results showed that zai pit combined with black plastic film mulch had the highest moisture content of 68.7%, which was 48% above the conventional farming method (FP). Among the un-mulched treatments (control), zai pits had the highest moisture content while conventional flat planting had the lowest. Within the individual farming systems, the moisture content varied significantly among the treatments; for instance, in ridge-furrow, the black plastic mulch had the highest increase of 34.8%, which was 5.2% higher than the transparent mulching film mulch, whilst the grass mulch had the lowest (10.6%). In conventional flat planting, the black plastic film mulch had the highest increase (24.8%), followed by transparent plastic film mulch (19.6%) and grass mulch (10.9%). Similarly, in zai pits, the black plastic film mulch had the highest increase (34.2%), which was 5.1% higher than the transparent plastic film mulch, while the grass mulch had the lowest increase (3.1%).

The study showed a significant ($P < 0.001$) yield increase of above-ground biomass among the mulched treatments (Table 1). Overall, the highest increase in biomass yield was found in the ridge-furrow with black plastic film mulch (178%) and the ridge-furrow with transparent plastic film mulch (176.6%), which were not significantly different. The lowest yield increase was found in the un-mulched flat and zai pit farming systems (control) and was not significantly different. Comparing the treatments in the individual farming systems, the results revealed that grass had a lower increase in biomass yield (36.9%) compared with black plastic film mulch (178%) and transparent plastic film mulch (176%). In conventional flat planting, the highest increase was found in black plastic film mulch (130%) followed by transparent plastic film (98.5%) and grass mulch (22%). In zai pit farming, the black plastic film recorded the highest increase (98.2%), followed by (86.3%), while the lowest was observed in grass mulch (2.4%).

Table 1. The effects of combined *in situ* water harvesting technologies on moisture content and above-ground biomass yield.

Treatment	Moisture content (%)	Biomass (kg ha ⁻¹)
T5	60.25c	3283.33a
T4	55.05d	3266.03a
T6	36.06f	1616.21f
RF	25.50i	1180.80 h
T2	45.45e	2610.33b
T1	40.25f	2250.66c
T3	31.50h	1383.33 g
FP	20.65j	1133.67j
T8	68.65a	2233.67d
T7	63.61b	2100.33e
T9	37.55g	1154.33i
ZP	34.50h	1127.10j
	LSD 1.36	LSD= 24.75
	P< 0.0001	P< 0.0001

Note: T5: ridge - furrow + black plastic film mulch, T4: ridge - furrow + transparent plastic film mulch, T6: ridge - furrow + grass mulch, RF: ridge - furrow with no mulching, T2: conventional flat planting + black plastic film mulch, T1: conventional flat planting + transparent plastic film mulch, T3: conventional flat planting +grass mulch, FP: conventional flat planting with no mulching, T8: zai pit + black plastic film mulch, T7: zai pit + transparent plastic film mulch (T7), T9: zai pit + grass mulch (T9), ZP: zai pit with no mulching. LSD = least significance difference, CV = coefficient of variation.

Means in the column followed by the different lower-case letters (a-j) are significantly different at ($P < 0.05$).

The effects of combined *in situ* water harvesting technologies on panicle length and number of tillers per plot

There was a highly significant ($P < 0.001$) effect of the mulching treatments on the increase of the panicle length among the treatments (Table 2). The overall results showed that compared with flat planting or the control, the ridge-furrow combined with black plastic film mulch had the highest increase in panicle length (141.4%) followed by ridge-furrow-plastic transparent mulch (118.4%) while the lowest increase was observed in zai pit combined with grass mulch (38.7%).

When treatments were compared based on the mulching type and farming system, we found that in the ridge-furrow, the black plastic mulch had the highest increase in panicle length (88.7%), followed by the transparent plastic mulch which had an increase of (70.8% while grass mulch had

the lowest increase (22.6%) compared with RF. The highest increase in flat planting was observed in black plastic mulch (109.6%), followed by transparent plastic mulch (96.1%) and grass mulch (47.4%) compared to FP. Similarly, in zai pits, the black plastic film mulch outperformed the other mulching treatments where the panicle size increased by (53.7%) compared to transparent plastic film and grass mulches which increased by (43.3%) and (17.7%) respectively.

Table 2. The effects of combined *in situ* water harvesting technologies on panicle length and number of tillers per plot.

Treatment	Panicle length (cm)	Number of tillers
T5	26.67a	34.33a
T4	24.13b	31.00b
T6	17.33g	12.13g
RF	14.13j	8.67i
T2	23.16c	28.33c
T1	21.67d	24.13d
T3	16.29h	10.13h
FP	11.05l	5.67k
T8	20.03e	16.67e
T7	18.67f	13.33f
T9	15.33i	11.13h
ZP	13.03k	7.33j
	LSD=0.94	LSD=1.24
	P< 0.001	P< 0.001

Note: T5: ridge - furrow + black plastic film mulch, T4: ridge - furrow + transparent plastic film mulch, T6: ridge - furrow + grass mulch, RF: ridge - furrow with no mulching, T2: conventional flat planting + black plastic film mulch, T1: conventional flat planting + transparent plastic film mulch, T3: conventional flat planting +grass mulch, FP: conventional flat planting with no mulching, T8: zai pit + black plastic film mulch, T7: zai pit + transparent plastic film mulch (T7), T9: zai pit + grass mulch (T9), ZP: zai pit with no mulching. LSD = least significance difference, CV = coefficient of variation.

Means in the column followed by the different lower-case letters (a-l) are significantly different at ($P < 0.05$)

Regarding the number of tillers, the overall results showed that the ridge-furrow with black plastic mulch had the highest increase (505.5%) in the number of tillers relative to FP, followed by the ridge-furrow with transparent mulch (446.7%), while conventional flat planting with grass mulch had the lowest increase (78.7%). Regarding the individual farming systems, we found that in ridge-furrow, the black plastic mulch had the

highest increase in the number of tillers (296%), followed by transparent plastic film mulch (257.8%), while the lowest was recorded in grass mulch (39.9%). Similarly, in flat planting, the black plastic mulch had the highest increase of the tillers (399.6%), followed by transparent mulch (3.25.6%), while the lowest increase was realized in grass mulch (78.7%). **Similar trend was observed** in zai pits, where the increase of tillers in black plastic mulches was notably higher (127.4%) than in transparent plastic film mulch (81.9%) and grass (51.8%).

The effects of combined *in situ* water harvesting technologies leaf area and plant height

The mulching treatments had highly significant ($P < 0.001$) effects in increasing both the plant height and stem girth (Table 3). The overall results showed that the ridge-furrow combined with the black plastic film mulch resulted in the highest increase in leaf area (176.1%) while the lowest increase was recorded in the zai pit combined with grass mulch (20%) and RF (17.1%) and was not significantly different. Based on the individual farming systems, the black plastic film mulch in ridge-furrow farming had the highest increase in leaf area (135.7%) followed by transparent mulch (74%) and grass (35.7%). In flat farming, the highest increase was found in black plastic film mulch (98.3%) followed by transparent plastic film (96.8%) and grass mulch (49.4%). Similarly, Zai-pit farming with the black plastic film mulches recorded the highest increase (54.9%) compared with transparent plastic film (38.1%) and grass mulches (3.5%). A non-significant increase in zai pits with grass mulch was noted.

With respect to the effect on plant height, the overall results showed that the two plastic film mulches recorded non-significant variations in plant height and had a higher increase compared with the grass mulch. The height among the treatments also varied significantly in the individual farming systems. For instance, in ridge-furrow, black plastic film mulches had a higher increase (6.4%) compared to plastic film mulches whose increase was lower (5.9%) although the difference was non-significant, while the grass mulch had the lowest increase (3.6%). Similarly, in flat farming, the difference in the increase of plant height in black plastic film (7%) and transparent plastic film mulch (6.6%) was not significant and was higher compared to grass mulch (4.4%). There was a significant increase in height in both the black plastic film mulches (3.4%) and plastic film mulch (3.5%) which was higher than in grass (1%).

Table 3. The effects of combined *in situ* water harvesting technologies leaf area and panicle weight.

Treatment	Leaf area (cm ²)	Plant height
T5	638.67a	187.87a
T4	471.67b	187.10a
T6	367.67c	182.96c
RF	271.00f	176.60f
T2	458.67b	186.23b
T1	455.33c	185.53b
T3	345.67e	182.13c
FP	231.33g	174.03f
T8	415.67d	185.23b
T7	370.67e	185.36b
T9	277.67f	180.87d
ZP	268.33f	179.13e
	LSD= 38.77	LSD = 1.58
	P< 0.0001	C.V = 2.07

Note: Note: T5: furrow - ridge-furrow + black plastic film mulch, T4: ridge - furrow + transparent plastic film mulch, T6: ridge - furrow + grass mulch, RF: ridge-furrow with no mulching, T2: conventional flat planting + black plastic film mulch, T1: conventional flat planting + transparent plastic film mulch, T3: conventional flat planting + grass mulch, FP: conventional flat planting with no mulching, T8: zai pit + black plastic film mulch, T7: zai pit + transparent plastic film mulch (T7), T9: zai pit + grass mulch (T9), ZP: zai pit with no mulching. LSD = least significance difference, CV = coefficient of variation.

Means in the column followed by the different lower-case letters (a-g) are significantly different at ($P < 0.05$).

DISCUSSION

The effects of combined *in situ* water harvesting technologies on moisture content and the above-ground biomass yield

The analysis of the crop growth and yields in numerous studies conducted in water-deficient semi-arid regions of Kenya has consistently reported lower yields of sorghum biomass under rainfed conditions. Both plastic and organic mulches prevent soil water evaporation to the atmosphere, and this increases crop transpiration (Li *et al.*, 2013). The highest increase in moisture content observed in zai pits combined with the black plastic film mulch may be attributed to their synergistic effects; the black plastic film significantly decreases both the soil temperatures and evaporation (Mo *et al.*, 2016), while zai pit increased water capture from the area surrounding the pits thus resulting to an increase in soil

moisture content. This study agrees with the previous studies by Nyamadzawo *et al.* (2013) in Zimbabwe, Mahadeen (2014) in Jordan, Malesu *et al.* (2006) in Kenya and Ren *et al.* (2016) in China who reported similar results.

The low moisture content observed in the conventional flat planting combined with grass mulch could be attributed to the low capture of runoff and incomplete ground cover which necessitated the loss of moisture through evaporation. The study findings corroborate with Lin *et al.* (2016) working in Loess Plateau, China, who found a lower increase in soil water content in organic mulch compared with plastic film mulches. The higher biomass yield in ridge-furrow combined with black plastic film mulches compared with the other treatments may be associated with their combined effects in improving the hydrothermal conditions of the soil which necessitated the increase of the biomass of the crop. Previous studies have shown that improved soil temperature and moisture, due to the use of plastic film mulching, increase leaf area, crop growth and aboveground biomass (Li *et al.*, 2013; Bu *et al.*, 2013).

Similar results have also been reported in earlier studies by Singh *et al.* (2013) and Gabir *et al.* (2014) in India and Ogbaga *et al.* (2019) in Nigeria who attributed higher sorghum biomass yields to the increase in the soil moisture content. On the contrary, the low increase of biomass in the zai pit farming system was due to water accumulation in the zai pits due to heavy rains experienced during the season. The month of April recorded the highest amount of rainfall which adversely affected the growth of the crops planted in the zai pits. There was frequent water accumulation in zai pits after rainfall, which adversely affected the growth of the crop and ultimately influenced the biomass yields. Waterlogged conditions have adverse effects on the growth of sorghum leading to early leaf senescence, reduced N uptake and metabolism, and retarded rate thus resulting in low biomass yield (Ren *et al.*, 2016; Ren *et al.*, 2017).

The effects of combined *in situ* water harvesting technologies on leaf area and plant height

The highest increase in leaf area observed in ridge-furrow farming systems combined with black plastic film mulch was attributed to high soil moisture content and reduced water loss through evaporation. Additionally, the increase in soil moisture and decrease in soil temperatures enhance optimal plant physiological processes (Mo *et al.*, 2016). Positive effects of increasing moisture content on the growth of leaves and

biomass have been observed by Makino (2011) in Japan and Mo *et al.* (2016) in Kenya. The conventional flat farming had the smallest size of leaves among the farming systems as a result of low moisture content since the soil was exposed to direct radiant energy which contributed significantly to moisture loss (Kinama *et al.*, 2005; Li *et al.*, 2018).

The mulched zai pits had the smallest leaf sizes and plant heights compared with other mulched farming systems (ridge-furrow and flat farming systems) which was attributed to the waterlogged conditions as a result of heavy rains during the vegetative stage of the crop. Ren *et al.* (2017) working in a state key laboratory in China have attributed high moisture content and water logging conditions to the loss of nitrogen and leaching of important nutrients in the soil. The current study, therefore, attributed the small leaf area and plant height in the zai pit farming system to the high amount of water collected during the rainy season

The effects of combined *in situ* water harvesting technologies on panicle length and number of tillers per plot

Soil mulching has been used to increase soil moisture content in dry lands for a long time. The increase in soil moisture level helps to sustain crop growth even during the intra-seasonal dry periods which coincides with vital crop growing stages. The observed increase in panicle length in ridge-furrow with black plastic mulch was attributed to adequate soil moisture content and the effect of the film mulch in decreasing the soil water evaporation and temperatures. **Previous** studies have shown that black plastic mulches are more effective in lowering soil temperatures than transparent films as they are more efficient in blocking some solar radiations besides decreasing water loss through evaporation (Li *et al.* 2013). **The current study** findings corroborate the earlier studies of Mutiso *et al.* (2018) in Kenya and Hu *et al.* (2020) in China. The low increase in panicle length and low number of tillers observed in the zai pit combined with black plastic film mulch could be attributed to water logging conditions caused by heavy rains during the crop growing season. A study by Ren *et al.* (2017) in China linked waterlogged conditions of soil to low accumulation of N in plants which affects plants' growth and performance.

CONCLUSIONS

The combined rainwater harvesting practices significantly increased biomass yield and morphometric parameters compared with the

single water harvesting methods (control). The increase in soil moisture content accelerated the crop growth, leaf size, panicle length, number of tillers and **above-ground** biomass yield. Precisely, the ridge-furrow farming system combined with black plastic film mulch had the highest biomass yield. Based on **these** findings, ridge-furrow film mulching is a promising technology **that** could improve rainwater harvesting and consequently improve the yield of sorghum biomass in semi-arid areas of Kitui County, and other areas with similar agroecological conditions. However, more studies are required on the economic feasibility of the technology considering the cost and the availability of the plastic films.

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Compliance with ethical standards. No consent was required and/or no authorization by an ethical or bioethical committee or equivalent declaration because the study did not involve human subjects.

Data Availability. The data is available with the first author – Boniface Mwami (mwami@ftz.czu.cz) upon reasonable request

Author contribution statement (CRediT)

B.M. Mwami - Conceptualization, formal analysis, methodology, visualization, software, writing – original draft, review and editing; **S.N. Nguluu, J.Kinama, R. Muasya** - Conceptualization, methodology, supervision; **A. Theuri, J. Wambua** – visualization and validation; **R. Muasya, B. Muli, A. Luvanda** - project administration, funding acquisition; **J. Kinama B. Muli, S.Nguluu, J. Kinama** - review and editing.

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