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Full Length Article

Enhancing Sorghum Grain Yield and Associated Attributes through *In Situ* Rainwater Harvesting and Soil Mulching in Semi-Arid Regions of Southeastern Kenya

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Abstract

Inadequate soil moisture constrains sorghum production in drylands leading to low yields. We conducted a study in Kitui County from 2nd October and 29th December 2021 to assess the impact of *In situ* water harvesting and soil mulching on grain yield and associated attributes of sorghum in semi-arid areas of south-eastern Kenya. The experiment was conducted in a randomized complete block design with 12 treatments comprising three farming practices (ridge-furrow, flat and zai pits) and three types of soil mulching materials (black plastic films, transparent plastic films and grass). The control treatments consisted of farming practices without mulching materials. The highest grain yield was observed in ridge-furrow with black plastic mulch (4498.33 kg ha^{-1}), indicating an increase of 41.4% compared to the lowest yield observed in conventional flat (3180.33 kg ha^{-1}). There was a non-significant difference in grain yield between flat planting with black plastic film mulch (4040.33 kg ha^{-1}) and flat planting with transparent plastic film mulch (3920.33 kg ha^{-1}). The moisture content was lowest in conventional flat planting (4.16 mm) and highest in zai pits with black plastic mulch (12.62 mm), indicating an increase of 203.4%. Plastic film mulches had a greater effect on increasing the grain yield attributes (panicle size, LAI, 1000 seed weight and stem girth) compared with the grass mulch. It was evident that black plastic mulching combined with ridge-furrow was the best combination for increasing grain yield; thus, their potential could be explored to increase food security in semi-arid areas of southeastern Kenya.

Keywords: Low yields; Cereals; Food security; Water stress; Dry tropics; Rain water harvesting

Introduction

Inadequate rainfall is the most limiting factor of crop production in semi-arid areas (Nguluu *et al.* 2014; Thierfelder *et al.* 2018). This has constrained sorghum production, particularly in semi-arid areas, resulting in a decline in yields (Kathuli and Itabari 2015; Shamme *et al.* 2016; Muui *et al.* 2019). Currently, sorghum production in Kenya's semi-arid lands is 0.5 ha^{-1} compared to yield potential of 4–7 t ha^{-1} (Abunyewa *et al.* 2017; Queiroz *et al.* 2018). Kenya primarily grows sorghum in drought-vulnerable marginal agricultural areas of the Eastern, Nyanza and Coast provinces (Muui *et al.* 2013). Sorghum production in these areas has remained low because people still prefer to grow maize, which is less ecologically adaptive compared to sorghum, paving the way to food insecurity (Dicko *et al.* 2006; Orr *et al.* 2016).

Most of Kenya's landmass is arid and semi-arid (ASALs), accounting for 89% of the total landmass (GOK 2015). Low rainfall primarily threatens crop yield in these

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areas (Ali *et al.* 2019). The soils in these areas have low water retention capacity and are more vulnerable to erosion, resulting in surface runoff (Kinama *et al.* 2007; Damene *et al.* 2013; Grum *et al.* 2017). Studies by Molden *et al.* (2007) and Senatilleke *et al.* (2022) exhibited that radiant energy in ASALs causes water loss by up to 90% of the total rainfall through evaporation, leaving only 10% for productive use by the plant. This is exacerbated by the inter-seasonal dry spells, which are common in ASALs (Mbanyele *et al.* 2021).

To address the aforementioned challenges, several management practices have been adopted, including soil mulching, ridging and furrowing, and the use of zai pits (Chen *et al.* 2013; Guo *et al.* 2014; Liu *et al.* 2018; Bucki and Siwek 2019; Niziolomski *et al.* 2020). Various types of mulching, including transparent plastic film, black plastic film, and straw or grass, have been used to grow different grain and fruit crops, such as maize, sorghum and sunflower (Luo *et al.* 2015; Fan *et al.* 2017; Zhao *et al.* 2016; Zhang *et al.* 2020). Studies have shown that mulching significantly increases grain yields and water use efficiency in ASALs (Mo *et al.* 2017, 2018; Wang *et al.* 2018). Different types of mulch or colours of plastic film mulches have different effects on crop growth. Various optical properties, including reflectivity, absorptivity, transmittance, and their interaction with solar radiant energy, directly affect the microclimate around the plant (Kasirajan and Ngouajio 2012). Regarding the transparent plastic film, light radiation can reach the soil surface directly, whereas the black plastic film has lower light permeability and radiative energy transmittance (Moreno and Moreno 2008). The straw mulching protects the soil surface from the direct effect of raindrops, promotes biological activity, reduces evaporation, and improves soil water content **(**Blanco-Canqui and Lal 2009; Yu *et al.* 2018). A study by Li *et al.* (2018a) showed a greater effect of black plastic mulch on increasing grain yield compared to transparent ones, while straw mulching is less effective compared to plastic mulching (Mo *et al.* 2018).

Rainwater Harvesting Practices (RWHPs) have demonstrated similar effects of increasing moisture content and grain yields. A study by Tamagnone *et al.* (2020) showed an increase in soil moisture content and rainwater infiltration by 87 and 100%, respectively using RWHPs. Previous studies have shown that organic mulching increases sorghum grain yield and maize yield by 55.6 and 60%, respectively (Kinama *et al.* 2005; Qin *et al.* 2015; Grum *et al.* 2017). A related study by Zhang *et al.* (2020) reported an increase in grain yields of maize and sorghum by 4.8 and 2.6 kg ha^{-1} mm^{-1}, respectively, using black plastic film mulches. Getare *et al.* (2021) reported an increase in sorghum grain yields in zai pits (3.06 kg ha^{-1}) compared to conventional flat planting (2.06 kg ha^{-1}). Similarly, Oduor *et al.* (2021) reported an increase in yield (853.33 kg ha^{-1}) in zai pits compared with conventional flat planting which recorded 685.0 kg ha^{-1}.

Despite the potential to increase grain yield, these techniques have setbacks; for instance, termites decompose the grass mulch, making it challenging to consistently maintain soil moisture. Moreover, the high ambient temperatures cause soil moisture loss through evaporation in moisture conservation structures such as zai pits and ridges during the intra-seasonal dry spells. It is therefore paramount to evaluate the synergistic effects of soil mulching and farming practices on grain yield and the associated components. Mo *et al.* (2017) reported a significant increase in maize yield on the East African plateau through combining ridge-furrowing and plastic mulching. In this study, we hypothesized that combining soil mulching and *in situ* RWHPs would significantly influence sorghum grain yield. The study's specific objectives were to: evaluate the effect of soil mulching on soil moisture content; assess the effect of soil mulching on grain yield; and determine the economic benefit associated with each treatment.

Materials and Methods

Study site and meteorological conditions

The experiment was conducted between 2nd October and 29th December 29, 2021, at the Demonstration and Research Farm of the South Eastern Kenya University (1 8 58.19" S, 37 43 47.86" E). The area is situated in Kitui County's Agro-Ecological Zone Lower Midland (AEZ LM4) of Kitui County at an altitude of 1105 m ASL (Jaetzold and Schmidt 1983a). It is very vulnerable to drought. It receives bimodal rainfall with an annual range varying between 500 and 1050 mm with 40% reliability and an annual mean temperature range between 25 and 30°C (ROK 2010; NAAIAP 2014). The county experiences high evaporation rates and a high amount of surface flow (Munyao *et al.* 2004; Muthomi *et al.* 2015). The most common soil types are acrisols, luvisols and ferralsols which are well-drained (Jaetzold and Schmidt 1983b).

Mean monthly rainfall distribution and air temperature during the growing season

The sorghum was sown before the onset of the short rainy season, which normally starts in October to December. The season was characterized by high temperatures, humidity, and rainfall. December recorded the highest amount of rainfall (159.18 mm) and specific humidity (14.34 g/kg) (Fig. 1). Specific humidity refers to the mass of water vapour in unit mass of moist air (expressed as grams of vapour per kg of air).

Treatments and experimental design

The experiment was conducted in a randomized, complete block design. The treatments consisted of three farming systems (conventional flat, ridge-furrow and zai pits) and

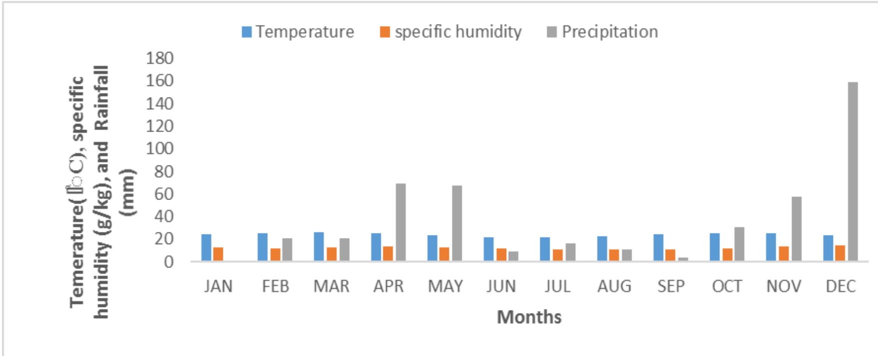

Fig. 1: Rainfall and temperature during the sorghum growing period in 2021 at South Eastern Kenya University, Kenya

three soil mulching materials (black plastic film, transparent plastic film and grass mulches). Farming practices without soil mulching served as control treatments. Three blocks were prepared, each measuring 324 m^2 (18 × 18 m) at a distance of 3 m. In each block, 12 sub-plots were established, each measuring 25 m^2 (5 × 5 m). Each subplot was surrounded by a furrow to control surface run-on.

Crop husbandry/field management

The experimental site was ploughed with a tractor-mounted disc plough at a depth of 30 cm. Soil clods were broken down to fine tilth and soil was levelled using hand-held hoes. Zai pits, ridge furrows and conventional flat planting plots were established accordingly before randomly distributing the mulching treatments. Precisely, nine zai pits measuring 0.6 m (width), 0.6 m (length) and 0.6 m (depth) were established in alternate rows and spaced at 0.6–0.8 m to increase water capture and reduce water runoff. Ridge furrows were prepared by shaping the soil surface into ridges and furrows measuring 45 and 20 cm in width and height, respectively. A total of eleven ridges and furrows were prepared in the respective plots. Similarly, in conventional flat planting, eleven furrows were established, measuring 45 and 20 cm. Farmyard manure was manually applied at a rate of 30 tons per hectare in all plots. The plots were then mulched accordingly two days before planting with either plastic or dry grass at a rate of 5 t ha^{-1}. The plastic mulches, measuring 70 cm wide and 0.008 mm thick, were applied to the soil and carefully covered around the edges to prevent strong winds from shifting them. Holes were made in the film at 0.4 m (inter-row) and 0.3 m (intra-row) to permit the planting of sorghum (*Sorghum bicolor* cv. Gadam) at a rate of 7 kg ha^{-1} and a depth of 2–4 cm. The same seed rate and depth were maintained in grass-mulched and un-mulched plots.

There were minimal management operations during the crop-growing period. Weeds were manually controlled at various phenological stages during the crop development (two weeks after germination, at the booting stage and two weeks after panicle initiation). Weaver birds (*Quelea quelea*) were controlled by scaring from the dough stage until harvesting and no incidence of diseases was noted during the sorghum growing period. No irrigation, pesticides, or herbicides were applied during the experimental period.

Data collection

Soil moisture content: In flat and ridge-furrow farming practices, the soil samples were collected near the root zone of plants in four middle rows at a depth of 0 – 0.25 m and an interval of 2 m weekly. Similarly, the samples were collected in zai pits, near the root zone of the plants in the middle row at a depth of 0.25 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, then wet weight taken, and oven dried to a stable weight at 105°C, according to Okalebo *et al.* (2002). The percentage moisture content (%) was computed as follows:

$$\text{Soil moisture content }(\%)\ \frac{\text{Wet weight (g)} - \text{oven dry weight}}{\text{Oven dry weight (g)}} \quad \text{equation 1}$$

Water use efficiency (WUE) was calculated as grain yield per unit of water received between planting and harvesting (in-crop rainfall) as follows:

$$\text{WUE (kg/mm)} = \frac{\text{grain yield (kg/ha)}}{\text{Total rainfall (mm)}} \quad \text{equation 2}$$

Plant sampling and measurement

LAI, panicle size, grain yield, 1000 seed weight, and girth: In each plot, 10 plants were randomly sampled at the sixth leaf during the booting, dough and physiological maturity of the plant to measure the aforementioned parameters. The leaf area and the stem girth were measured using a tape measure, at the booting and half-bloom stages. Leaf area was calculated according to Birch *et al.* (1998) (length × leaf width × 0.75). The leaf area index (LAI) was then calculated as the ratio of leaf area to ground area.

The panicle size (cm^2) was determined by measuring the panicle width at the middle of the ear head (the widest section) of 10 randomly selected fresh panicles per plot using a tape measure. The panicle's length was measured from its bottom to its top. The length was multiplied by the width to compute the panicle size.

At physiological maturity, four rows (equal to 6 m^2) in the middle of each plot were harvested by cutting sorghum panicles at the base using a knife and sun-drying them to a grain moisture content of 13% before threshing them manually. The grains were then put in bags, weighed taken and computed in kg ha^{-1} at 13% grain moisture content in all treatments. A 1000 g weight was then determined by physically counting 200 dry grains randomly subsampled from each plot sample and weighing them in grams using a digital weighing balance. The weight was then multiplied by 5 and expressed as 1000 g, according to Saha *et al.* (2007).

Economic analysis

Gross margins were calculated to assess the economic benefits of different treatments. The production costs included labour including tractor hire, seeds and the costs of mulching materials. The labour cost of each treatment is composed of man-days spent on preparing the land, planting, weeding, spreading mulching materials, and harvesting sorghum by casual workers hired to perform these operations. The same workers were always used to carry out the activities on each experimental plot during similar times of the day. The timing of the activities was done without the knowledge of the workers. On each task, the beginning time, number of people involved and finishing time were recorded. The average number of hours for all workers was converted into monetary value using a local standard wage of US$3.09 per person per day covering 8 h. During the study period, the cost of mulching materials and seeds was determined by the market price. In each treatment, the economic benefit was calculated as the difference between the price of sorghum grain yield (US$) and the cost of production.

Statistical analysis

The data collected was subjected to an analysis of variance (ANOVA) using the GLM procedure in SAS version 9.4 (SAS 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 effect of mulching and farming practices on soil moisture content, sorghum's grain yield and the associated yield components

Soil mulching significantly ($P < 0.001$) increased the soil moisture content, water use efficiency, grain yield as well as its associated components in the three farming practices compared with the un-mulched treatments (control) (Table 1). In ridge-furrow farming system, the interaction between ridge-furrow and black plastic mulch resulted in the highest moisture content (80.83%), followed by ridge-furrow x transparent plastic mulch (58.42%) and ridge-furrow x grass mulch (19.47%). In flat planting, the black plastic film mulch increased soil moisture content by 137%, followed by transparent plastic film mulch (128.4%) and grass mulch (28.8%). The black plastic film mulch had the highest moisture content (84.77%), while grass mulch (24.89%) had the lowest compared to the control in zai pits.

The overall results showed that zai pits combined with black plastic film mulch had the highest moisture content (12.62 mm), which was an increase of 203.37% compared with flat planting, commonly known as the farmers' practice. Among the three farming practices without mulching treatments, the zai pit exhibited the highest increase in moisture content (6.83 mm), which was 5.56 and 64.18% higher than the ridge-furrow and conventional flat farming, respectively.

The combination of ridge-furrow and black plastic mulching showed the highest increase in water use efficiency (WUE), which was 48.7% above the un-mulched ridge-furrow (control). Similarly, in flat farming, the interaction of flat farming and black plastic mulching resulted in the highest WUE (41.2%) relative to the conventional flat farming method. In zai pits, the effect of combining transparent plastic mulch was stronger, translating to the highest WUE (10%) compared to the control. Overall, the study found the interaction of ridge-furrow and black plastic mulch resulted in the highest increase in WUE (57.2%).

The study recorded an increase in grain yield in all treatments across the farming systems. In the ridge-furrow farming system, the ridge-furrow x black plastic mulch interaction yielded the highest increase in grain yield (48.59%) compared to un-mulched ridge-furrow (control). Similarly, in flat farming, the black plastic film mulch had the highest grain yield increase (41.11%) compared with grass mulch (15.23%), which had the lowest. Compared to the ridge-furrow and flat farming systems, the interaction of zai pits with transparent plastic mulches resulted in the highest increase in grain yield at 14.45%, followed by black plastic film mulch at 9.97% and grass mulch at 2.255%. Overall, the ridge-furrow with black plastic film mulch produced the highest yields (4498.33 kg ha^{-1}), indicating an increase of 4.67% compared to transparent plastic mulch (4297.67) and 41.44% higher than the grass mulch (3180.33 kg ha^{-1}). Farming practices without mulching showed that the zai pits had the highest grain yield (3110.33 kg ha^{-1}), which indicated an increase of 2.74% compared with ridge-furrow (8.63%), while flat planting, which farmers practice, recorded the lowest. We found a non-significant difference in grain yield between non-mulched zai pits and ridging.

The highest increase in panicle size (43.79%) was observed in ridge-furrow and black plastic mulch, while the

Table 1: The effects of mulching and farming practices on soil moisture content and grain yield of Sorghum

Treatments	Farming practice	Grain yield, kg ha^{-1}	Moisture content, mm	Water use efficiency (kg ha^{-1} mm)	panicle size (cm^2)	LAI	1000 seeds weight (g)	stem girth (cm)
BPM	Ridge - furrow	4498.33a	11.70b	9.65a	152.63 a	498.31a	20.86a	1.54a
TPM	Ridge - furrow	4297.67b	10.25c	9.22b	146.00b	471.67a	19.93b	1.50a
GM	Ridge - furrow	3680.00d	7.73g	9.89a	114.80e	344.37b	18.60c	1.26d
R	Ridge - furrow	3027.33h	6.47i	6.47d	106.15g	376.33d	15.16e	1.02e
BPM	flat planting	4040.33c	9.86d	8.67b	119.51c	448.67b	18.60c	1.44b
TPM	flat planting	3920.33c	9.50e	8.41b	118.67c	415.67c	18.20c	1.43b
GM	flat planting	3299.67f	5.36j	7.08c	110.50f	332.67e	16.36d	1.28d
F	flat planting	2863.33i	4.16k	6.14e	102.51h	266.66f	11.30g	1.01e
BPM	Zai pit	3420.33e	12.62a	7.34c	117.37d	254.33f	15.40d	1.37c
TPM	Zaipit	3559.67d	11.60b	7.64c	116. 57e	396.67c	15.96d	1.41b
GM	Zai pit	3180.33g	6.83h	6.82d	109.31f	312.33e	14.73e	1.05e
Z	Zai pit	3110.33 h	8.53f	6.67d	109.20f	293.56e	13.46f	1.03e
		LSD 191.55	LSD 0.36	LSD 0.64	LSD 2.62	LSD 29.37	LSD 0.82	LSD 0.04
		C.V = 2.07	C.V = 2.07	C.V = 2.07	C.V = 2.07	C.V = 2.07	CV = 2.07	CV = 2.07

Note: BPM: black plastic film mulch, TPM: transparent plastic film mulch, GM: grass mulch, R: ridge-furrow with no mulch (control), F: flat planting with no mulch, (control) Z: zai pit with no mulch (control)
LSD = least significance difference, CV = coefficient of variation
Means in the column followed by the different lower-case letters are significantly different at ($P < 0.05$)

lowest increase (8.15%) was observed in grass mulch x ridge-furrow interaction. In flat farming, there was no significant difference between the increase in panicle size in black plastic mulch (16.58%) and transparent plastic mulch (15.76%). The grass mulch showed a lower increase of panicle size (7.79%) compared with transparent and black plastic mulching.

In zai pit farming, the highest increase in panicle size (0.07%) was found in zai pit combined with black plastic mulch, while the lowest (0.1%) was registered in zai pits with grass mulch which was not significantly different from the control. Overall, among the mulched treatments, the interaction of the ridge furrow x black plastic film mulch resulted in the largest panicle size (152.63 cm^2), which was a 39.63% increase compared with the zai pit x grass mulch (109.31 cm^2), which had the smallest size. Among the non-mulched treatments, zai pit farming had the highest panicle size (109.20 cm^2), indicating an increase of 2.87% compared with the ridge-furrow and 6.53% relative to flat planting.

In ridge-furrow farming, the LAI was highest in black plastic and transparent plastic mulches and was not significantly different. On the other hand, grass mulch demonstrated the lowest increase which translated to 31.87% compared with the control. The combined effect of flat farming and black plastic film mulch exhibited the highest increase in LAI (76.41%), followed by transparent plastic film mulch (63.44%), and grass mulch (30.80%). Transparent plastic film mulch showed the highest increase (35.12%) in the zai pit, followed by black plastic film mulch (28.02%) and grass mulch (6.39%). Among the un-mulched treatments, ridge-furrow had the largest LAI (376.33), showing an increase of 28.20 and 3.63% in comparison to zai pit and flat planting, respectively.

The ridge-furrow with black plastic film mulch recorded the highest increase (84.60%) in weight of 1000 grains, compared with the grass which recorded the lowest (21.29%) relative to conventional flat planting. In flat planting, the 1000-grain weight in the two plastic film mulches was not significantly different and was higher than in the grass mulch. Similarly, the interaction of zai pit x black plastic mulch and zai pit x transparent plastic mulches had a greater effect of increasing the weight of 1000 grains, compared with grass mulch, and were not significantly different.

The study showed an increase in stem girths in all farming practices. We found the highest increase in stem girth in ridge-furrow with black plastic film mulch (50.98%) and transparent plastic film mulch x ridge-furrow (47.06%), and they were not significantly different, while grass mulch exhibited the lowest increase (23.53%). In flat planting, the stem girth had the highest increase in the black plastic film mulch (42.57%), followed by transparent plastic film mulch (41.58%), and grass mulch (26.73%), respectively. In the zai pit, transparent plastic film mulch had the highest increase in stem girth (368.9%), followed by black plastic film mulch (33%), and grass mulch (1.94%), which did not vary significantly from the control.

Economic benefits of the treatments

Combining ridge-furrow with black plastic mulch exhibited the highest economic benefit (US$ 2270.5), which translates to a 49.1% increase above the un-mulched ridge-furrow control (Table 1). Combining conventional flat planting with back plastic mulches resulted in the highest economic benefit (US$ 2037.6) in conventional flat farming compared with transparent plastic and grass mulches. The interaction of transparent plastic mulches with zai pits showed a higher economic benefit (1793.2), translating to an increase of 14.6% compared to the control. Overall, a combination of black plastic mulch and ridge furrow had the highest economic returns of US$ 2270.5 ha^{-1} (Table 2.). This translates to a 57.8% increase compared with conventional flat planting, which had US$ 1439.1.

Table 2: Economic benefit of sorghum under different treatments

Input values of consumables items (USD ha^{-1})						Output value of sorghum grain yield (USD ha^{-1})	Economic benefit
Treatment	Farming practice	Cost of Labour	Cost of seeds	Cost of mulching	Total cost	Total	
BPM	Ridge-furrow	15.83	0.5	0.5	16.83	2287.3	2270.5
TPM	Ridge-furrow	15.83	0.5	0.5	16.83	2185.3	2168.5
GM	Ridge-furrow	15.83	0.5	0.5	16.83	1871.1	1854.3
R	Ridge-Furrow	16.05	0.5	0	16.55	1539.3	1522.5
BPM	Flat planting	15.83	0.5	0.5	16.83	2054.4	2037.6
TPM	Flat planting	15.83	0.5	0.5	16.83	1993.2	1976.4
GM	Flat planting	15.83	0.5	0.2	16.53	1677.8	1661.0
F	Flat planting	15.83	0.5	0	16.33	1455.9	1439.1
BPM	Zai pit	17.66	0.5	1.5	19.66	1739.2	1722.4
TPM	Zai pit	17.66	0.5	1.5	19.66	1810	1793.2
GM	Zai pit	17.66	0.5	0.2	18.36	1617.1	1600.3
Z	Zai pit	17.66	0.5	0	18.66	1581.5	1564.7

Note: BPM: black plastic film mulch, TPM: transparent plastic film mulch, GM: grass mulch, R: ridge-furrow with no mulch (control), F: flat planting with no mulch, (control) Z: zai pit with no mulch (control)

Discussion

The present study showed that non-mulched treatments had lower grain yields relative to the mulched plots. This indicates the positive effects of mulching treatments on increasing the moisture content, which is vital for proper growth and ultimately increases grain yields (Jabran *et al.* 2015). This is confirmed by a study by Mo *et al.* (2017), which found a direct relationship between the application of mulches and an increase in grain yield. The observed increase in grain yield in plastic mulch compared to grass mulch in the present study suggests the superiority of plastic mulching in preserving soil moisture. This has been reported earlier in studies by Mo *et al.* (2018). Additionally, previous studies by Li *et al.* (2013) and Bu *et al.* (2013) have associated the increase in grain yield with improved soil hydrothermal conditions. The lowest moisture content observed in the conventional farming system was expected, as the soil was exposed to direct radiant energy, resulting in the loss of moisture through evaporation. Mulching provides a barrier that prevents the loss of water vapour to the atmosphere, leading to a reduction in soil water loss (Jabran *et al.* 2015). Thus, mulches prevent soil water loss by reducing evaporation (McMillen 2013). The observed low moisture content in the flat farming system could also be due to the fact that there was low water capture for runoff and surface flow compared to ridges-furrow and zai pits. This has earlier been reported in the study by Lin *et al.* (2016).

The highest increase in grain yield in ridge-furrow combined with black plastic film mulches could be attributed to the architecture of the ridge-furrow system, which has shown to be effective in rainwater harvesting where water from the ridges is directed to the furrows and consequently the root zone of the plant. This improves the soil's hydrothermal conditions and boosts plant physiological processes. Additionally, the black plastic mulches prevent solar energy from reaching the soil surface, creating better hydrothermal conditions for the plant and leading to higher grain yields. These findings are confirmed by an earlier study by Mo *et al.* (2016), who reported similar findings.

The lower yields reported in the zai pits were expected due to the heavy downpour experienced during the season, which resulted in water accumulation in the pits. The massive accumulation of water in the zai pit in December was noted when the rainfall was at its peak (Fig. 1) which had negative effects on sorghum and thus resulted in low yields. We attributed the low yields to the low uptake of nutrients caused by leaching and denitrification. This has previously been reported in the studies of (Nevison *et al.* 2016; Ren *et al.* 2017; Tian *et al.* 2021). Our study corroborates previous studies by Wafula *et al.* (2022) and Mwami *et al.* (2024) associate low grain yields in water logging conditions with leaching and denitrification.

In addition to grain yield, soil mulching significantly increased WUE. We observed that, compared with conventional flat farming, both transparent and black film mulching treatments increased WUE significantly. This is in line with the earlier findings of Mo *et al.* (2017), who found higher WUE in maize grown in mulched treatments compared with the control. Plastic film mulching increases the WUE because it reduces soil water evaporation and increases plant transpiration (Jia *et al.* 2006; Wu *et al.* 2017). By attenuating the flow of water from deeper soil layers to the topsoil through vapour transfer and capillarity, mulching abates soil water evaporation, consequently maintaining relatively stable water content in the topsoil (Tian *et al.* 2003; Wang *et al.* 2009). Such stable soil water content likely enhances plant productivity and WUE. Under rain-fed conditions, as is the case for our study, soil mulching enhances rainwater harvesting and facilitates infiltration, thus ensuring sufficient soil moisture near the plants' root zone (Kar and Kumar 2007; Arora *et al.* 2011), which could explain the reason for increased WUE under plastic mulching. The un-mulched treatment in conventional flat-planting farming had a lower WUE, possibly due to higher soil water evaporation and poor soil conditions. Higher soil evaporation potentially affects the grain productivity of sorghum by reducing soil water supply in critical growth and developmental phases.

We attribute the difference in panicle size in different mulching treatments to differences in soil moisture content. Previous studies have shown that soil mulching is effective in supporting plants even during inter-season dry spells (Gabir *et al*. 2014; Muñoz *et al*. 2017). Our study found the highest increase in panicle size in ridge furrows with black plastic film mulch, which we attributed to efficient water harvesting by the ridges and the plastic film mulch. The increase in panicle size has earlier been reported in related studies by Mo *et al.* (2016) and Katiyar *et al.* (2021).

The study found that mulched treatments had higher LAI than un-mulched treatments, indicating that mulching plays an important role in supporting plant growth. Our finding corroborates the previous studies of Zhang *et al.* (2011) and Zhao *et al.* (2014), who reported similar results. According to Bakshi *et al.* (2015) and Muñoz *et al.* (2017), the reported increase in LAI in plastic film mulches combined with ridge-furrow may be associated with reduced soil temperature and increased soil moisture. We attributed the low LAI under grass mulch treatment to insufficient ground cover, leading to more water loss through evaporation as compared to plastic mulch, which provides complete soil cover. Earlier studies have demonstrated that black plastic mulches are more efficient at blocking some solar radiation and decreasing water loss through evaporation (Li *et al.* 2013). Our study attributed the small LAI in the zai pit to the massive accumulation of water in the pits during the crop-growing period. This significantly affected the growth of sorghum, leading to a small yield. We attributed this to the possible loss of nutrients through leaching and denitrification, as elucidated in the studies of Nevison *et al.* (2016) and Mwami *et al.* (2024).

The observed increase in seed weight in ridge-furrows with black plastic film mulch above other treatments could be associated with better soil hydrothermal conditions, which is vital for supporting plants' growth and its physiological processes. This agrees with the previous findings of Mwithiga and Sifuna (2006) and Naim *et al.* (2018), who reported similar results. Sufficient soil moisture has been associated with optimal seed filling and bolder grains with higher weight (Naim *er al.* 2018; Bonane 2019). This could explain why the 1000 seed weight in conventional flat farming was low compared to mulched treatments. The reported differences in the stem girth in our study could be associated with the differences in soil water content between the treatments. The low rainwater harvesting potential of flat planting resulted in low moisture content, which might have resulted in small stem girths (Li *et al.* 2018; Mwami *et al.* 2024). On the other hand, the increase in stem girth in ridge-furrow combined with black plastic film mulch could be attributed to adequate soil moisture during the crop-growing period. We therefore associate the increase of stem girth with an increase in soil moisture content and reduced soil temperatures. This is in agreement with the previous findings of Mo *et al.* (2017). Other previous studies have also associated the increase in stem girth with the increase in soil moisture content (Easson and Fearnehough 2000; Ashrafuzzaman *et al.* 2011; Bucki and Siwek 2019).

Economic profitability determines if a beneficial agronomic practice can be adopted by the farmers. In this study, the output value of plastic film mulching was considerably higher than that of non-mulched treatments. Compared to non-mulched treatments, plastic mulching requires additional plastic film and labour. However, non-mulched treatments also required more labour for weeding. Other crops like maize, cabbage, and cotton have also reported similar results (Paranhos *et al.* 2016; Zhang *et al.* 2017a, b; Li *et al.* 2018b). The zai pits combined with plastic mulch had the highest input costs compared with other treatments due to the costs of digging the pits and the mulching materials. On the other hand, conventional flat farming had the lowest input costs because it didn't require any treatment. Our study showed that the ridge furrow with black plastic mulch had the highest economic returns. This is due to the high yields, which offset the costs incurred (Mo *et al.* 2017; Bhatta *et al.* 2020). We found a low economic benefit for the un-mulched ridge-furrow compared to the mulched ones, which is consistent with a study by Li *et al.* (2018a), which reported similar findings.

In this study, we acknowledge that the ridge-furrow and black plastic mulch resulted in the highest grain yield, WUE, and economic benefit. However, there are some limitations to using plastic mulch. The long-term use of plastic film may lead to large number of residues that are difficult to degrade and may cause environmental problems (white pollution) (Gao *et al.* 2019; Prata *et al.* 2019). Plastic film residues are difficult to completely remove, leaving the majority in the soil where they interfere with mechanical tillage, threaten the health of cattle and sheep, damage the soil structure, and delay root development, all of which can be detrimental to sustainable agriculture (Fan *et al.* 2019; Gao *et al.* 2019). To improve the agricultural environment, this practice requires interventions through the development of innovative covering materials. Biodegradable plastic film or straw mulching can also significantly improve the soil environment and crop yield (Hou and Li 2019; Prata *et al.* 2019).

Conclusion

The ridge-furrow combined with black plastic mulching had the highest grain yield, WUE and economic benefit compared with the other treatments. Although zai pits had the highest water content its grain yield, WUE and economic benefits were low compared with other treatments due to the detrimental effects of water accumulation in the pits during the season. The grain yield attributes were higher in mulched treatments compared with unmulched ones due to improved soil hydrothermal conditions. Our findings suggest that combining black plastic films with ridge furrow could be explored to increase sorghum grain yields in semi-arid areas of southeastern Kenya.

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Author Contributions

Each author (BM, RM, SN JK BM, AL, AT, JW and XY) equally contributed as main contributors to the design and conceptualization of the manuscript, performed the analysis, prepared the initial draft, and revised and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

All authors declare no conflict of interest.

Data Availability

Data presented in this study will be available on a fair request to the corresponding author.

Ethics Approval

Not applicable to this paper.

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