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Comparison of different mulching options for improving water productivity and maize yield in a semi-arid climate, Northern Ethiopia, Tigray

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Abstract
This study compared the effectiveness of organic and inorganic mulching options for improving soil moisture content (SMC), water productivity (WP), and maize yield. The objectives of the study were to (a) investigate the effects of organic and inorganic mulches on SMC and water productivity, (b) quantify maize yield improvements due to the application of organic and inorganic mulches. The experiment was set up with a randomized complete block design with four treatments, namely black plastic mulch (BPM), white plastic mulch (WPM), flax straw mulch (FSM), and a control. The result indicated that WPM, BPM, and FSM increased maize yield by 66.1, 47.0, and 1.9% compared to the control. The net returns with the application of WPM, BPM and FSM were 1459.0, 1119.6, and 847.1 USD/hectare, respectively. Similarly, WPM, BPM, and FSM increased WP by 184.5, 127.6, and 39.4%, respectively. SMC was also increased by 16, 10.8, and 3.5% by WPM, BPM, and FSM, respectively. Inorganic mulches had a significant effect on WP and maize yield. On the other hand, FSM did not have any significant effect on WP and maize yield. The findings of this study indicated that inorganic mulches are useful for improving WP and maize yield. It is therefore necessary to apply inorganic mulches to improve WP and maximize maize yield in areas with a semi-arid climate such as northern Ethiopia.

Keywords Plastic mulch · Soil moisture content (SMC) · Straw mulch · Water productivity (WP)

1 Introduction

Poor irrigation management, financial constraints, lack of market accessibility, environmental and social impacts were the main causes for the development of only 5% of Ethiopia's irrigation potential [1]. Traditional agricultural practices have contributed to the low productivity of the agricultural sector [2]. Efficient use of limited water resources, especially for irrigation, will enhance the producer's yield per unit of water and hinder negative effects on the environment, such as drainage problems and salinity resulting from overuse of water [3].

One of the main causes for low productivity of crops in arid and semi-arid areas is the occurrence of moisture stress during plant growth. Among others, covering crop land with mulch creates a sustainable irrigation period because it reduces moisture stress during plant growth [4]. Regardless of its type, mulch prevents erosion [5] and improves soil water content [5, 6]. Soil moisture content (SMC) depends on weather conditions and the effect of mulching on SMC varies from year to year irrespective of the mulch type [7].

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Covering soils with mulch increases water productivity (WP) in arid and semi-arid areas in the dry season [6]. It however brings no significant difference when applied in the rainy season [8, 9]. Mulching helps to increase crop yield and yield components, particularly in water-stressed arid and semi-arid areas [10]. Mulch was found to increase crop yield components [11] and gave higher number of grains per cob compared to no mulch [8]. In other study, mulch produced significantly fewer cobs but had a higher overall crop yield [7]. Black plastic mulch and no mulch gave similar yield results under limited irrigation, but plastic mulch produced a higher grain yield than no mulch under adequate irrigation practice [12]. Another study by Ramalan et al. [13], however, found that there is a significant difference in crop yield for white and black mulches. Although straw mulch is also found to improve yield and yield components of maize, its negative impact can overweigh its benefits if the straw mulch level is significantly increased and it is not managed properly [14].

There are several studies conducted to assess the effect of mulching on WP and maize crop yield components under irrigation and rain-fed agriculture. Mupangwa et al. [15], for example, studied the effect of organic mulches on maize growth and yield in sub-humid climate under natural rainfall conditions. Yuan [16] investigated the effect of film mulch on WP and maize crop yield under both irrigation and rain-fed cultivations in Ethiopia. Cai et al. [17] studied the effects of different types of straw mulch on soil water storage and WP of spring maize in the Loess Plateau of China. Similarly, Jelde and Berhanu [18] explored the effect of straw mulch and manure on moisture conservation, yield and yield components of maize in a dry agro-climatic zone. Zhang et al. [19] investigated the effect of plastic film mulch on maize yield and economic return in semi-arid climates. Another study by Rani et al. [8] explored the effect of straw mulch and irrigation levels on WP, growth and yield of maize. There are also other similar studies; for example, the effect of plastic mulch on WP and maize growth [9], the effect of mulching on maize yield [20], the effect of straw mulching on water consumption characteristics and yield [21], the impact of tillage and mulching on soil hydrothermal conditions [22], crop yield and weed management [23], the effect of different types of mulches on maize yield and weed flora [24], and maize growth, yield and water use [6]. These studies however were not comprehensive because either they missed incorporating both organic and inorganic mulch types or they were conducted on rain-fed agricultural practices. These researchers also did not consider WP, SMC and semi-arid climate as the main focus of the study. Moreover, some of these studies were focused on either maize yield components or WP. To comprehend the overall benefit of mulches, it is necessary to investigate the effect of both organic and inorganic mulches on maize yield and yield components. Furthermore, the benefit of different types of mulches on improving WP need to be assessed under irrigation systems. Thus, this study evaluated the effect of different mulch materials (organic and inorganic) on SMC, WP, maize yield and yield components. Therefore, the objectives of the study were; (a) to investigate the effect of organic and inorganic mulches on SMC and WP, (b) to quantify maize yield improvements due to the application of organic and inorganic mulches in an irrigated system. The study was applied in semi-arid northern Ethiopia under an irrigated system with the application of black plastic mulch, white plastic mulch, flax straw mulch and a control with no mulch.

2 Materials and methods

2.1 Experimental site description

The field experiment was conducted at Mekelle University, College of Dry Land Agriculture and Natural Resources, Land Resources Management and Environmental Protection (LaRMEP) experimental site during February to June 2020. The site is located in northern Ethiopia, Tigray region (13°28′35″N and 39°29′13″E (Fig. 1). The study site has an average elevation of 2210 m above sea level. The soil type of the study site is sandy loam.

The study area has a semi-arid climate with a uni-modal rainfall pattern. Rain usually begins in May and gradually increases to reach its maximum in July and August. Annual rainfall for the study area (1992–2018) ranged from 256 to 753 mm (Fig. 2). The temperature of the study is moderate and relatively uniform throughout the year (Fig. 2). Although the rainfall pattern of the study area is unimodal it shows temporal and spatial variations. As a result, rainfall variation significantly affects the rain-fed agricultural production and WP of the study area. Since the existing agricultural system of the study area is mainly rain-fed, farmers suffer from shortage or temporal variability of rainfall during crop growth periods.

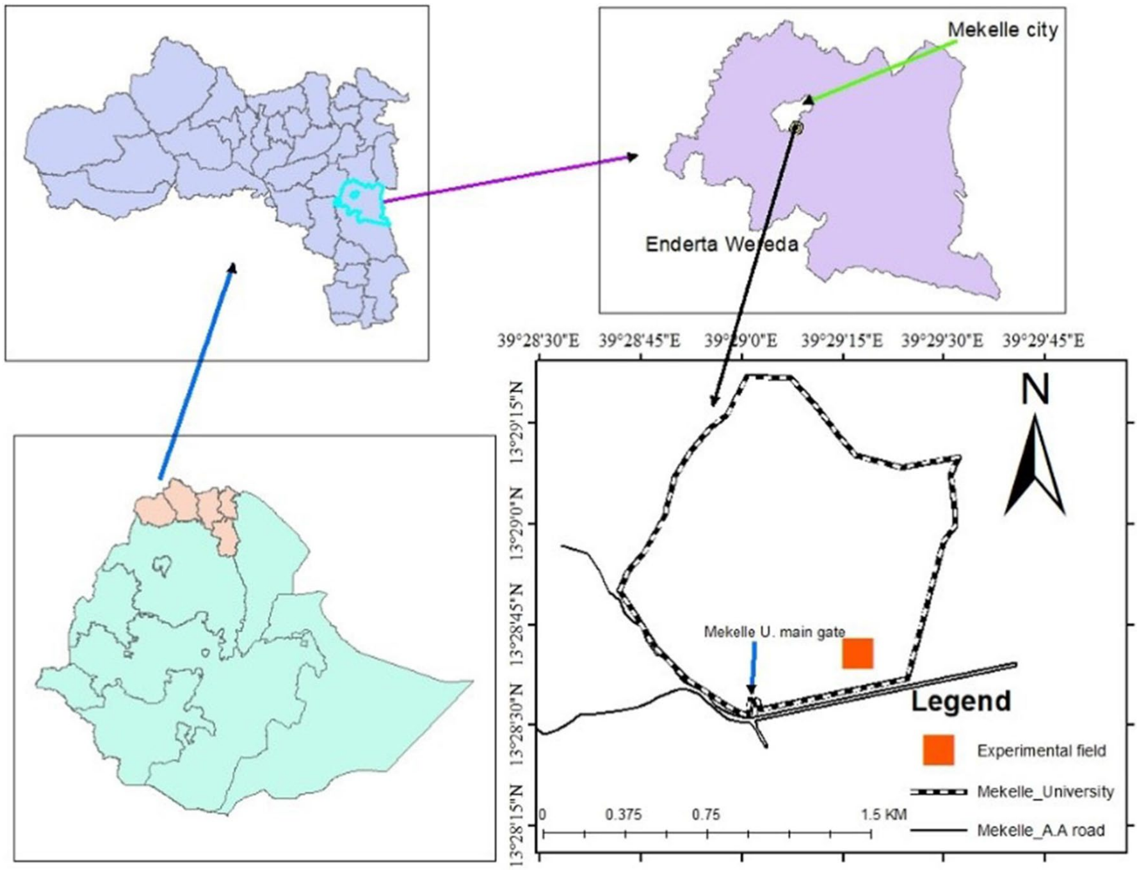
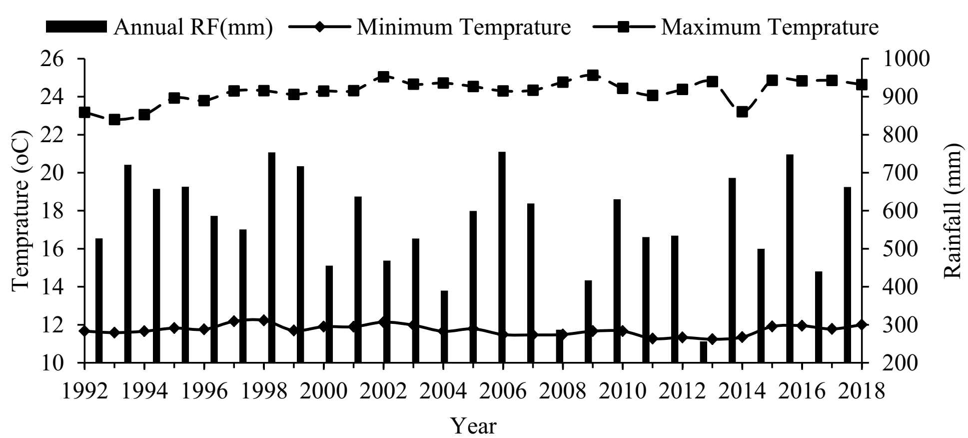


Fig. 1 Study site location map

Fig. 2 Annual rainfall (RF), minimum and maximum temperatures for the study area



2.2 Field preparation and experimental design

During site preparation, all plots were ploughed using local plough to remove all weeds. Then, the beds for the experimental plots were cleaned, smoothed and leveled. Three blocks, or replicates were prepared for the experimental study. As a result, 12 experimental plots were prepared for four treatments. The distance between consecutive blocks was 100 cm while the distance between consecutive plots was 50 cm. The experiment had a completely randomized block design consisting of four treatments including a control. A completely randomized block design (CRBD) is one of the standard designs for agricultural experiments. In a CRBD, similar experimental units are grouped into blocks or replicates. Each block has the same size and equal number of treatments. Each treatment was randomly assigned

Table 1 Description of experimental treatments

Treatment	Description	Thickness/weight of mulch	Application rate per hectare	Diammonium phosphate (DAP)/urea application rate per hectare
Co	Control (no mulch)	–	–	112.5 kg
BPM	Black plastic mulch	12 µm	12,100 m^2	112.5 kg
WPM	White plastic mulch	12 µm	12,100 m^2	112.5 kg
FSM	Flax straw mulch	8 kg	20,000 kg	112.5 kg

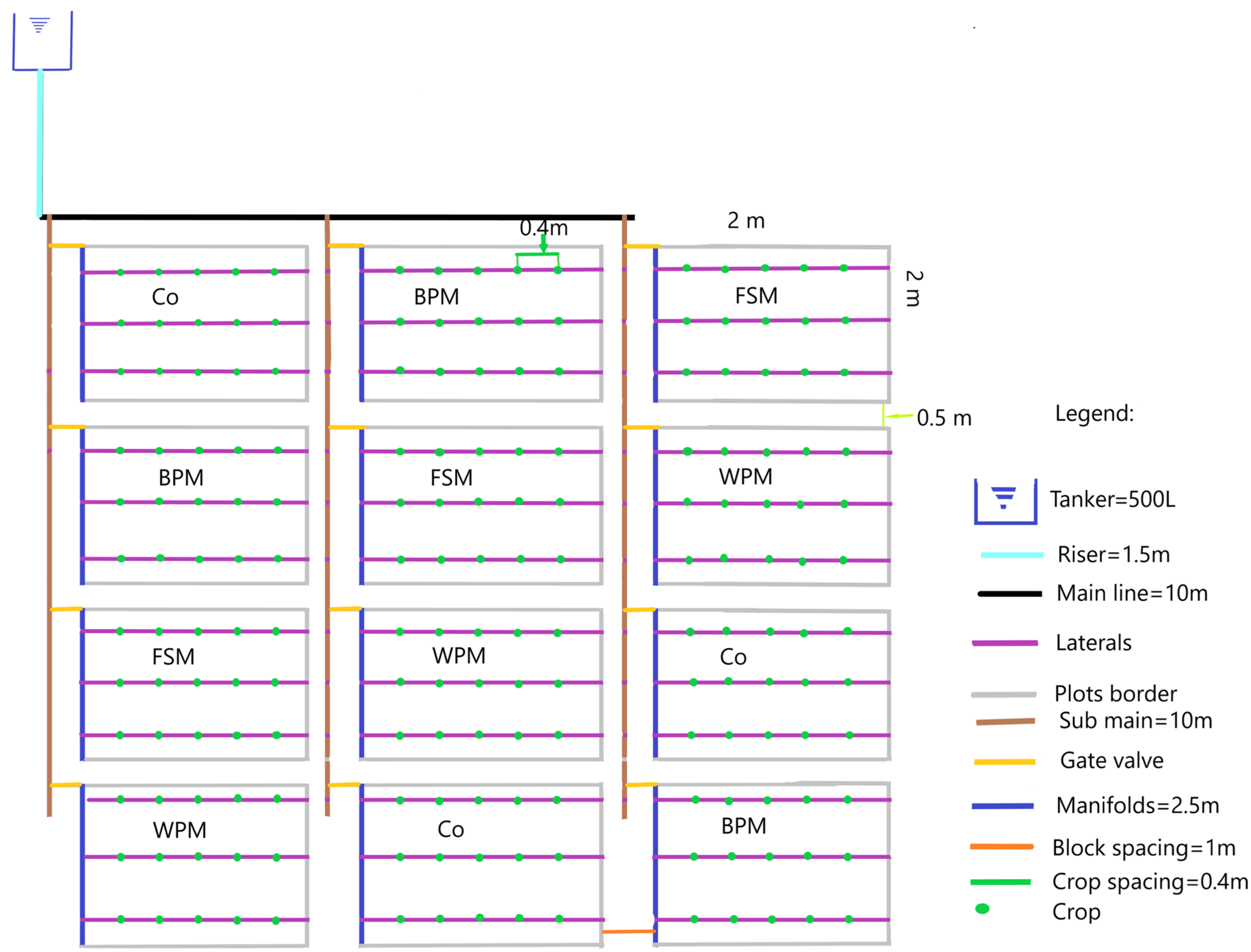


Fig. 3 Lay out of the experiment with four treatments and three replicates. *BPM* black plastic mulch, *WPM* white plastic mulch, *FSM* flax straw mulch, *Co* control

to exactly one experimental unit within every block. In this experiment, there were 3 blocks, and 4 treatments in each block. The treatments were black plastic mulch (BPM), white plastic mulch (WPM), flax straw mulch (FSM) and a control (Co) with no mulch. The effective individual plot size was 2 m by 2 m with an area of 4 m^2. The description of the experimental design is summarized in Table 1.

Each experimental plot had 3 laterals, 5 drippers per lateral, and one crop per dripper. The spacing between drippers (crops) was kept at 40 cm. Since one dripper feeds one crop (plant) and the dripper spacing is 40 cm, the spacing between plants or crops was similarly 40 cm (Fig. 3).

After site preparation, mulching materials for the experimental plots were placed onsite on February 11, 2020. The maize plant was sown on February 13, 2020. Figure 4 shows the crop status during the field experiment. The maize plant was finally harvested on June 4, 2020.

2.3 Data collection and analysis

2.3.1 Soil moisture content (SMC)

SMC was determined by taking fresh soil sample from depths of 0–30 cm and 30–60 cm in the experimental field at every irrigation interval. Although geographic location, soil and climatic conditions influence plant growth, du Plessis [53] indicates that maize root often extends beyond 30 cm. The samples were taken at a distance of 10 cm from the dripper. Sampled fresh soils were weighed and dried in an oven for 24 h at 105 °C. The gravimetric SMC was determined using Eq. 1.

$$SMC(\%) = \frac{FSW - DSW}{DSW} \times 100 \quad (1)$$

where SMC is soil moisture content (%), FSW is fresh soil weight (kg) and DSW is dry soil weight (kg).

To measure the soil characteristics, disturbed and undisturbed soil samples taken at different depths using augers and core sampler were analyzed in an agriculture physical soil laboratory to determine the field capacity, permanent wilting point, bulk density, texture and moisture content of the existing soil. Soil texture was determined using hydrometer method. Field capacity and permanent wilting point were determined using pressure plates at 3 bar and 15 bar pressures, respectively.

2.3.2 Water productivity (WP)

WP is the yield of dry matter per quantity of water used to produce a crop [8]. It was determined using Eq. 2.

$$WP\left(kgha^{-1}mm^{-1}\right) = \frac{Grain\ yield\left(kgha^{-1}\right)}{water\ use(mm)} \quad (2)$$

The water use was measured based on the water requirement and dripper flow rate, and the duration of irrigation time. Gate valves were used to control the flow of water into the irrigated plots. SMC was measured at each irrigation

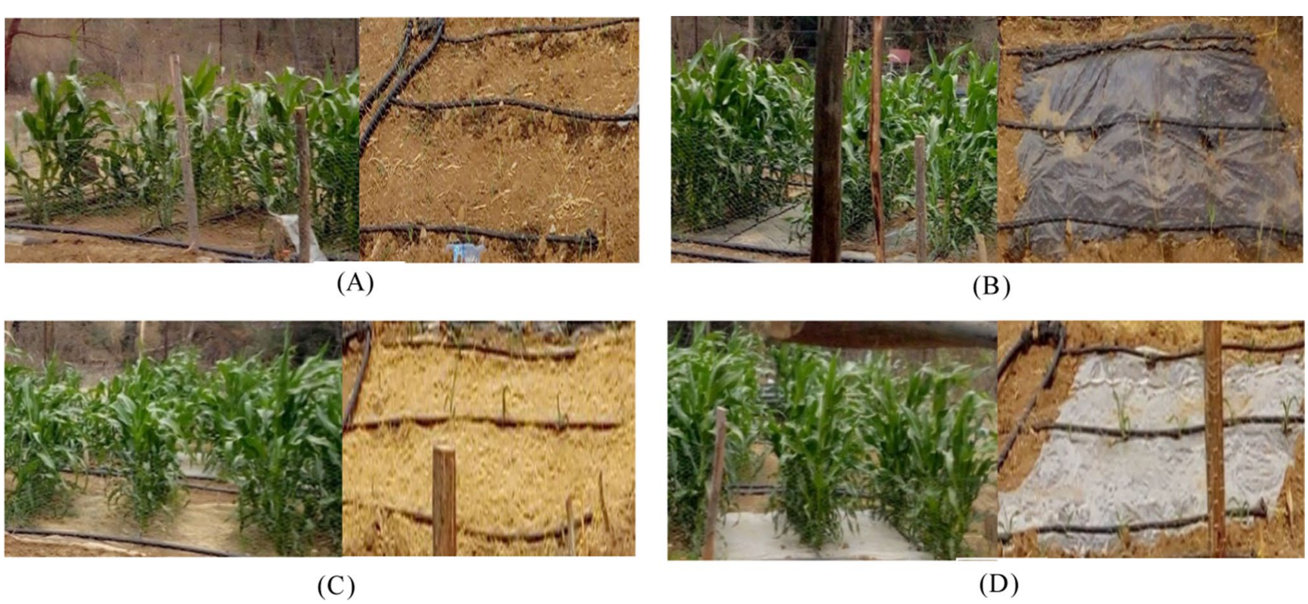


Fig. 4 Photograph of different treatments in the field experiment, **A** control (no mulch), **B** black plastic mulch, **C** flax straw mulch and **D** white plastic mulch

time. Based on the current SMC, water requirement and duration of irrigation time were scheduled for each treatment. The amount of water used for each treatment considering the net area was determined in Liter per net plot area. Then the volume of water used per treatment per plot was converted into Liter per hectare.

2.3.3 Economic analyses

The economic analysis included computing the total costs of the experiment and the total benefits

gained by using treatments involving organic and inorganic mulches. The economic analysis considered field preparation, ploughing, water application, treatment material, material installation, labour and transportation expenses or costs. Benefits were enumerated from crop production or yield.

$$Gross\ return\left(\frac{\$}{ha}\right) = \sum all\ incomes \tag{3}$$

$$Benefit\ cost\ ratio(B : C) = \frac{Gross\ return(\$/ha)}{Total\ cost(\$/ha)} \tag{4}$$

2.3.4 Irrigation water requirement

The amount of irrigation water applied was calculated using CROPWAT 8.0 using necessary input data such as crop type, soil and long-term climatic data. Irrigation water was applied up to field capacity by monitoring SMC using gravimetric method in the drip irrigation system for all irrigation intervals.

From the CROPWAT 8.0 result, the seasonal gross irrigation and net irrigation water requirements for maize crop were 566.7 and 510.1 mm, respectively. The seasonal water requirement for maize crop ranges from 400 to 750 mm [25]. Hence, the calculated amount of seasonal irrigation water requirement for this study was within the recommended irrigation water requirement for the maize crop.

Data collection is the backbone of any research. In this study, tape meter and ruler were used to measure the crop components (i.e. stem height, stem diameter, cob diameter, cob length, leaf length and width). The counting method was used to record tasseling, earing and silking dates. The grain yield and biomass of maize were measured using weight balance. The crop component data were collected at 15 days interval. All data for measured variables were recorded in checklist and Microsoft Excel (version 2010).

2.4 Statistical analysis

Statistical data analysis was done using IBM SPSS Statistics 20. The normally distributed data were analyzed using a parametric test, i.e., one-way analyses of variance (ANOVA). The data that were not normally distributed were analyzed using a non-parametric test, i.e., the Mann–Whitney U test. Differences were considered significant when the p value was less than 0.05 (95% confidence level). The mean comparisons between the significant effects in ANOVA were made using the Tukey test.

2.5 Human and animal rights

During the implementation of this research, the violation of human and animal rights is highly prohibited.

3 Results and discussion

3.1 Soil physical properties

The field capacity of the soil on a mass basis ranged from 22.49 to 32.29%. Similarly, the permanent wilting point of the soil varied between 9.77 and 10.59%. The average field capacity and permanent wilting point were 28.7% and 10.2%

Table 2 Soil physical properties of the experimental site (n = 3)

Treatment	BD (gcm^3)	FC (%)	PWP (%)	Sand (%)	Silt (%)	Clay (%)	Textural classification
Co	1.28	29.28	10.37	69.67	15.33	15.00	Sandy loam
BPM	1.34	32.29	10.05	63.67	18.00	18.33	Sandy loam
WPM	1.59	22.49	10.59	66.00	16.33	17.67	Sandy loam
FSM	1.22	30.82	9.77	68.67	16.33	15.00	Sandy loam
Mean	1.36	28.72	10.20	67.00	16.50	16.50	Sandy loam

BD Bulk density, *FC* field capacity, *PWP* permanent wilting point, *Co* Control (no mulch), *BPM* black plastic mulch, *WPM* White plastic mulch, *FSM* flax straw mulch

Table 3 Effect of mulch on soil moisture content (n = 3)

Treatment	Soil moisture content (%), mean ± SD
Co	12.59 ± 0.35^{a}
BPM	13.95 ± 0.79^{ab}
WPM	14.60 ± 0.74^{b}
FSM	13.04 ± 0.56^{ab}
P	0.018

Different letters show significant (Tukey-test, $p < 0{\cdot}05$) differences between treatments, a < b. *Co* control, *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch

respectively with total available moisture of 252.03 mm. The bulk density of the soil varied from 1.22 to 1.59 g/cm^3. The oil texture of the experimental site was sandy loam and was similar in all plots and treatments (Table 2).

3.2 Soil moisture content (SMC)

The effect of different mulches on SMC, which was measured before each irrigation interval for the whole irrigation season, is shown in Table 3.

The findings of this experiment (Table 3) indicated that, there is an overall significant ($p < 0.05$) effect of treatments on SMC. The mean SMC varied from 12.59 to 14.60%. The minimum and maximum SMCs were observed in the control and white plastic mulch, respectively. White plastic mulch produced significantly higher SMC than the control. However, black plastic and flax straw mulches did not significantly improve SMC compared to the control. Thus, the mean moisture content was maximum in white plastic mulch (14.60%) followed by black plastic mulch (13.95%), straw mulch (13.04%) and the control (12.59%).

As shown in Fig. 5, SMC was higher in plots with mulch materials than the control. Overall, white plastic mulch had the highest SMC compared to the other mulch materials and the control. The role of mulch on moisture conservation was not constant in each irrigation interval. For the first 4 irrigation intervals (initial stage) and the last 13 irrigation intervals (mid and late season), white plastic mulch conserved a higher amount of moisture than the other treatments, because it did not consume the incoming sunlight, rather it reflects and saves the water content that was consumed by the reflected sunlight. From 5 to 8 irrigation interval (development stage), BPM conserved a higher amount of moisture compared to the other treatments. For all treatments, the minimum moisture content was recorded during the initial application time and the maximum moisture content was recorded during the 9th irrigation application time. The maximum moisture contents during the 9th and 13th irrigation application times were because of the sudden occurrence of natural rainfall events. SMC during the 9th and 13th irrigation application times were 19.52 and 18.71% for WPM, 18.73 and 17.94% for BPM, 18.91 and 17.99% for FSM, and 18.52 and 16.83% for the control, respectively. Similar to this result, Kwambe et al. [26] reported that white (clear) plastic mulch conserved a higher amount of moisture content compared to black plastic mulch, grass mulch and a control. In other studies, straw mulch [27] and plastic film applied for three consecutive years [28] were found to increase SMC compared to no mulch. Another study by Monks et al. [29] showed that there was only small but significant differences (76–84%) in moisture content between mulched and non-mulched soils in the first 2 weeks after planting. A similar study by Gul et al. [30] indicated SMC in plots with mulch had significantly increased at the 9th week after planting. The highest SMC was conserved by shredded newspaper on average (37.67%) followed by

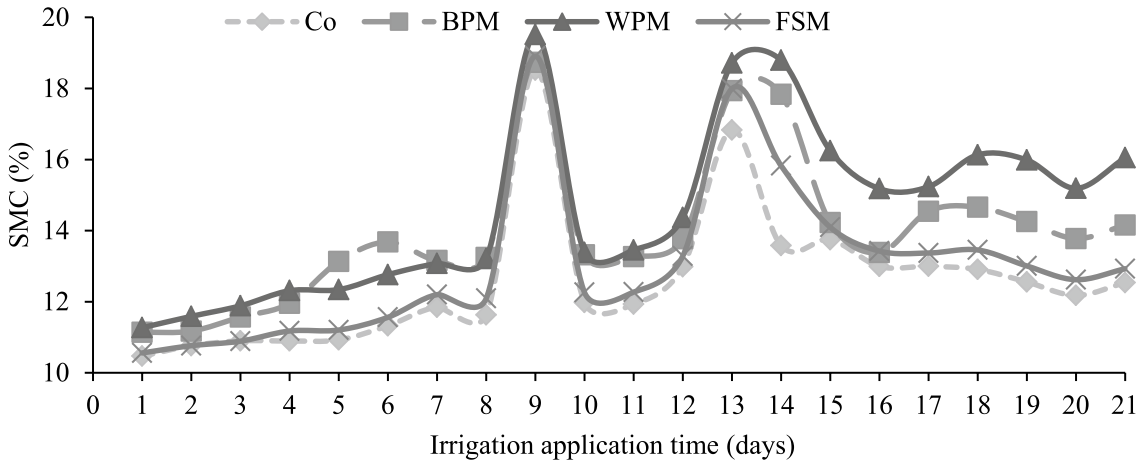


Fig. 5 Soil moisture content (SMC) variation with time for different treatments. Co: Control (no mulch); BPM: Black plastic mulch; WPM: White plastic mulch; FSM: Flax straw mulch

wheat straw mulch (34%), black plastic mulch (30%), and a control [29]. Similarly, Chakraborty et al. [12] demonstrated that SMC was the highest in black plastic mulch (13%) followed by rice straw (12%) and white transparent plastic mulch (11.9%) at harvest time.

3.3 Development of crop components

3.3.1 Stem height and stem diameter

Crop height and diameter progressively increased with the age of the crop up to harvest time, irrespective of the treatments. The progressive development of crop height and crop diameter was measured every 15 days throughout the irrigation season. There was significant ($p < 0.05$) effect of treatments on stem height. The mean stem height varied from 4.71 to 8.79 cm (initial stage), 43.44 to 72.27 cm (development stage), 126.8 to 170.69 cm (mid stage) and 127.51 to 171.67 cm (late stage). The minimum and maximum stem heights were observed in the control and black plastic mulch, respectively (Fig. 6).

Black plastic mulch showed a high mean stem height increment at the development stage followed by white plastic mulch. Although the increment amount was different, the maximum mean height increment was observed during the development stage (Table 4).

Plant height was maximum in black plastic mulch followed by white plastic mulch, straw mulch and the control. In line with this finding, maize crop height increased in black plastic mulch by 171 cm followed by weed mulch (162 cm) and white plastic mulch (161 cm) [30]. Similarly, tomato crop height was significantly increased in black plastic mulch by 77.2 cm followed by white plastic mulch (74.6 cm) and straw mulch (62.8 cm) [31]. Several studies [11, 26, 32, 33] have confirmed that plant height significantly increases with the application of mulch on soil compared to bare soil. Contrary to this, Meskelu et al. [34] reported no significant effect of mulch and irrigation water levels on crop height.

The result indicated that there is a significant ($p < 0.05$) effect of treatments on stem diameter (Table 5). The minimum and maximum stem diameters were observed in the control (week 2) and white plastic mulch (week 8), respectively. The minimum and maximum observed stem diameters were 3.7 and 30.7 mm, respectively. Similar to this finding, Ni et al. [11] also revealed a significant effect of mulch on tea olive stem diameter.

The agronomic data were collected every 15 days (2 weeks). Even though crop height consistently increased with time of crop development SMC and crop diameter were not consistently increasing with time of crop development (Figs. 7, 8).

3.3.2 Effect of mulch on tasseling, earing and silking

The tasseling, earing and silking maize components started to develop during the development stage and ended at the beginning of mid-season days. The effect of different mulches on crop tasseling, earing and silking maize components, which were measured at the first day of their development, are shown in Fig. 9.

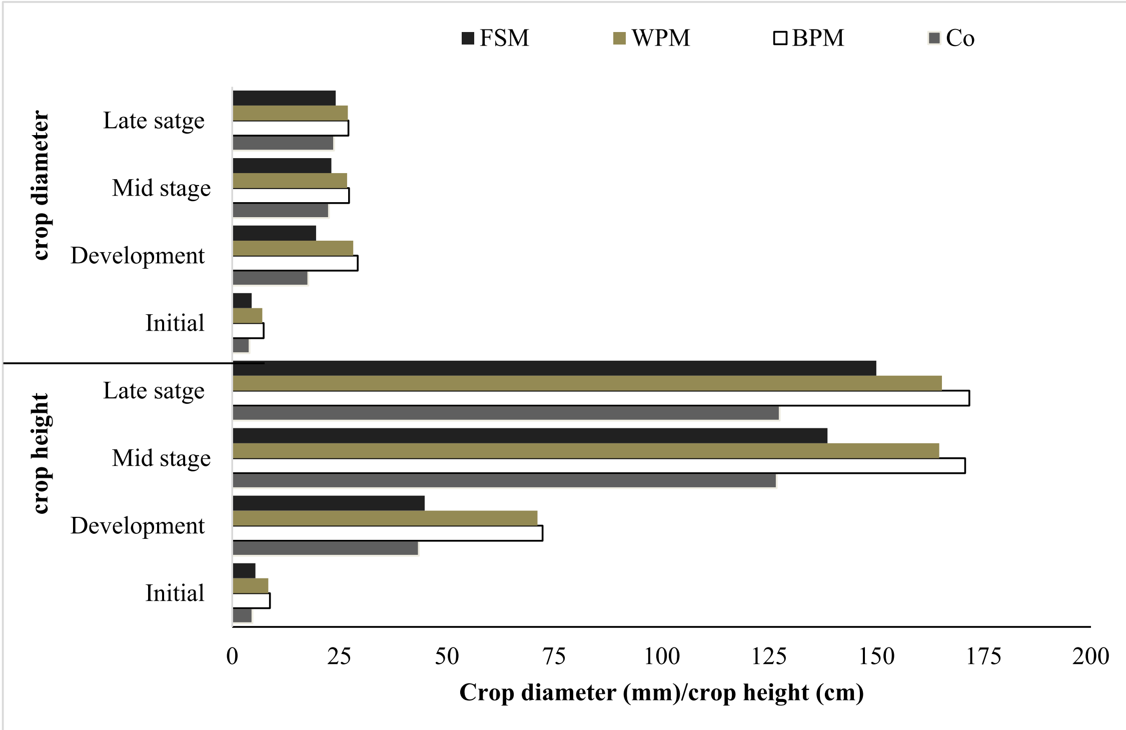


Fig. 6 Crop height and diameter at each growth stage

This result (Fig. 9) shows a significant ($p < 0.05$) effect of treatments on the number of days for earing and silking. The maximum and minimum earing and silking durations were observed in the control and black plastic mulch, respectively. However, flax straw mulch took the maximum duration for tasseling and white plastic mulch took the minimum duration for tasseling. The mean earing and silking days were minimum in black plastic mulch (53.7, 57.04 days) followed by white plastic mulch (54.93, 58.67 days), flax straw mulch (62.07, 65.02 days) and control (62.71, 65.98 days). However, the minimum tasseling duration was observed in white plastic mulch (52 days), followed by black plastic mulch (55 days), control (59 days), and flax straw mulch (60 days). The number of days becomes short in plastic mulches, because the plastic mulches keep high temperature, reduce weeding and conserve water content. These conditions accelerate the emergence of the crops.

The entire emergence was achieved within the development stage in black and white plastic mulches. Emergence was achieved within the first few days of the mid-season for flax straw mulch and the control. Babatunde and Etukundo [31] also reported that emergence was first achieved for black polyethylene plastic mulch (44 days), followed by white polyethylene plastic mulch (46 days), straw mulch (53 days), and control (57 days). The number of days for tasseling and silking were minimum for both black and white plastic mulches (56 days), followed by straw mulch (57 days), and the control (60 days) [30]. On the other hand, Ibrahim and Khan [35] found that the number of days for tasseling and silking were minimum in clear (transparent) plastic mulches followed by colored and residue mulches. Generally, Rani et al. [8] reported that the durations for tasseling was minimum for mulched plant growth compared to no mulch.

3.4 Effect of mulch on grain yield and yield components

3.4.1 Number of cobs and grains per crop

The effect of different mulches on the numbers of grains, which was measured (using physical counting) after 3 days from harvest time are summarized in Table 6. The total number of grains indicates the sum of the main crop and tiller grain numbers.

The overall result showed a non-significant ($p > 0.05$) effect of treatments on the number of cobs and grains per crop (Table 6). On the other hand, there was a significant effect of treatments on the number of grains per crop. The number of median cobs per crop for the treatments varied from 1 to 2. Similarly, the number of median grains per crop for the

Table 4 Crop stem height (cm) for different treatments during 1 to 7 irrigation weeks (n = 45)

Treatments	Height-1, Median (Min, Max)	Height-2 Mean ± SD	Height-3 Mean ± SD	Height-4 Mean ± SD	Height-5 Mean ± SD	Height-6 Mean ± SD	Height-7 Mean ± SD
Co	4.37(3.73,6.02)[a]	15.64 ± 3.0[a]	43.44 ± 4.24[a]	92.11 ± 6.17[a]	115.31 ± 5.07[a]	126.8 ± 5.74[a]	127.51 ± 5.78[a]
BPM	10.39(5.5,10.47)[b]	29.38 ± 3.57[b]	72.27 ± 6.86[b]	148.56 ± 6.21[b]	162.44 ± 2.94[c]	170.69 ± 5.75[b]	171.67 ± 3.82[c]
WPM	9.7 (5.33,10.11)[b]	26.74 ± 8.37[b]	71.07 ± 21.69[b]	140.18 ± 29.24[ab]	152.22 ± 17.9[bc]	164.64 ± 10.06[b]	165.27 ± 9.78[bc]
FSM	6 (3.6,6.56)[a]	16.94 ± 5.9[a]	44.8 ± 9.51[a]	96.27 ± 20.82[a]	127.56 ± 3.89[ab]	138.61 ± 4.711[a]	149.99 ± 5.21[b]
P (0.05)	0.040	0.039	0.033	0.010	0.001	0.000	0.000

Different letters show significant (Tukey-test, $p < 0·05$) differences between treatments, a < b < c. *Co* Control, *BPM* black plastic mulch, *WPM* white plastic mulch, *FSM* Flax straw mulch; height-1 = height in week2; height-2 = height in week4; height– 3 = height in week6; height-4 = height in week8; height-5 = height in week10; height-6 = height in week12; height-7 = height in week14; for Height-1 (crop height in week 2) Mann–Whitney Test, $p < 0.05$ was adopted

Table 5 Crop stem diameter (mm) for various treatments (n = 45)

Treatments	Diameter-1 Median(Min,Max)	Diameter -2 Mean ± SD	Diameter-3 Mean ± SD	Diameter-4, Median (Min, Max)	Diameter-5 Mean ± SD	Diameter-6 Mean ± SD	Diameter-7 Mean ± SD
Co	3.73 (3.37,5)^{a}	10.31 ± 1.37^{a}	17.71 ± 2.76^{a}	20.13 (19.2,21.13)^{a}	21.29 ± 0.86^{a}	22.51 ± 0.14^{a}	23.71 ± 0.25^{a}
BPM	8.83 (4.23,8.87)^{b}	20.16 ± 1.23^{b}	29.22 ± 0.102^{b}	21.07 (18.93,23.73)^{a}	26.33 ± 1.33^{b}	27.2 ± 1.3^{b}	27.07 ± 1.56^{b}
WPM	8.37 (4.0,8.67)^{b}	18.91 ± 4.2^{b}	28.16 ± 1.18^{b}	30.73 (25.07,30.8)^{b}	26.62 ± 1.23^{b}	26.76 ± 0.8^{b}	26.93 ± 0.95^{b}
FSM	4.3 (3.07,6.17)^{a}	10.32 ± 1.66^{a}	19.53 ± 2.37^{a}	29.73 (27.6,32.53)^{b}	22.2 ± 1.09^{a}	23.07 ± 0.07^{a}	24.09 ± 0.32^{a}
P(0.05)	0.040	0.001	0.000	0.040	0.001	0.000	0.003

Different letters show significant (Tukey-test, $p < 0·05$) differences between treatments, a < b < c. *Co* Control, *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch; Diameter − 1 = Diameter in week2; Diameter − 2 = Diameter in week 4; Diameter − 3 = Diameter in week6; Diameter − 5 = Diameter in week10; Diameter − 6 = Diameter in week12; Diameter − 7 = Diameter in week14; for Diameter-1 (diameter in week 2); Diameter-4(diameter in week 8) Mann–Whitney Test, $p < 0.05$ is adopted

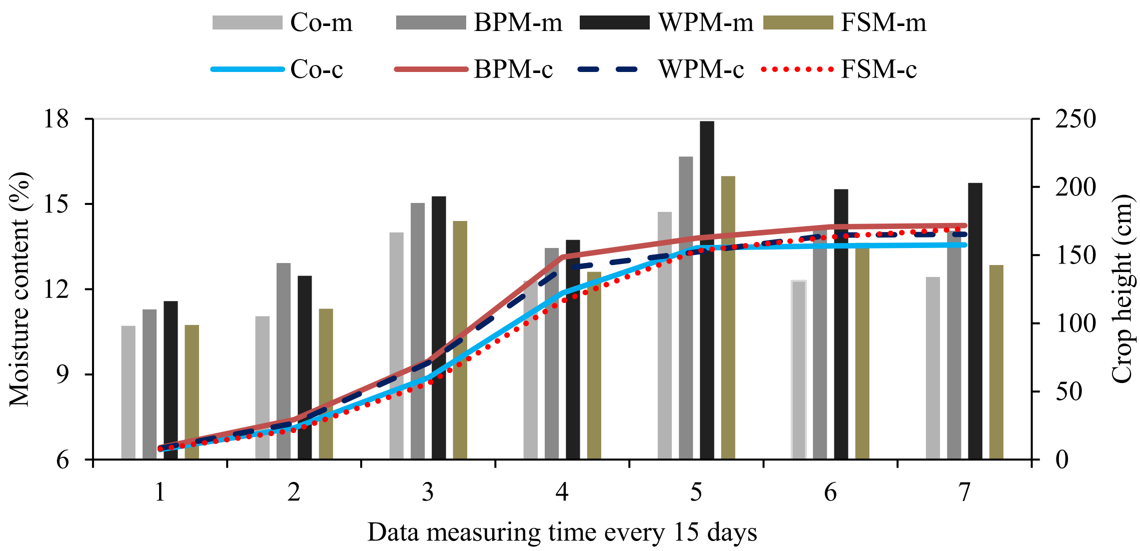


Fig. 7 Crop height development and moisture content variations. *Co* Control (no mulch), *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch, *m*: moisture content at corresponding mulch, *c*: crop height development at corresponding mulch

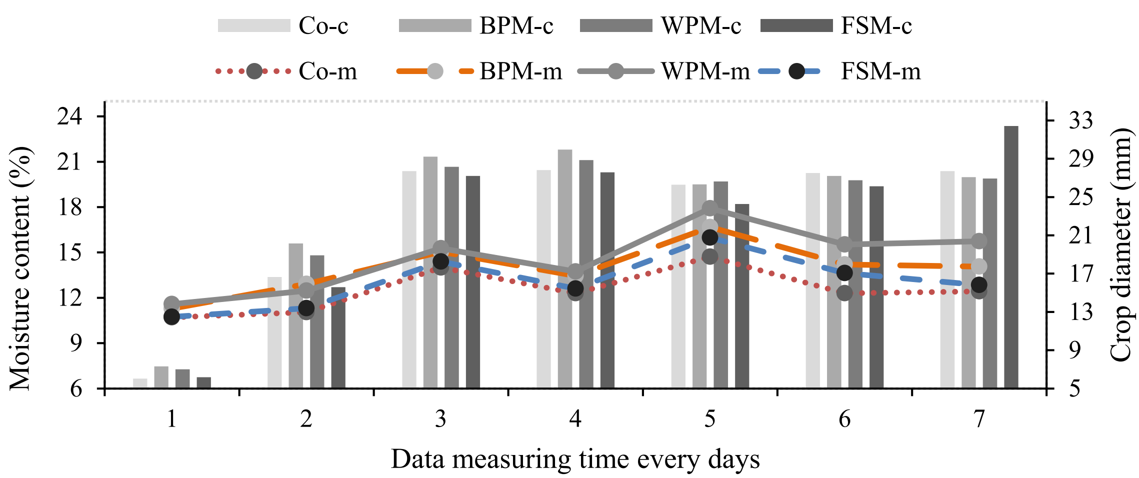


Fig. 8 Crop diameter development and moisture content variations for various treatments. *Co* Control (no mulch), *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch, *m*: moisture content at corresponding mulch, *c*: crop diameter development at corresponding mulch

Fig. 9 Effect of mulch on number of days to tasseling, earing and silking per crop. Different letters show significant (Tukey-test, $p < 0.05$) differences between treatments, a < b. *Co* Control, *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch

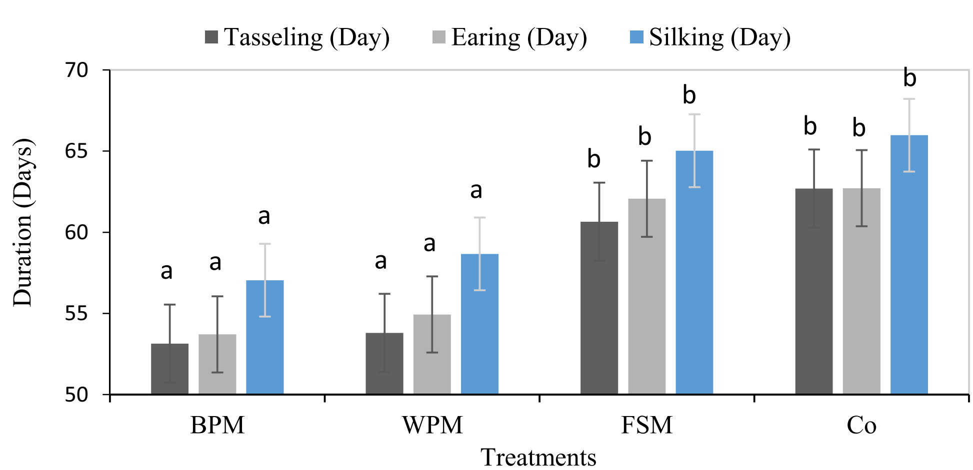


Table 6 Effect of mulch on total number of cobs and maize grains for various treatments (n = 45)

Treatment	Number of cobs per crop, median (min, max)	Number of grains per crop, median (min, max)
Co	1 (0,3)[a]	632 (288,1286)[a]
BPM	2 (1,2)[a]	931 (226,1772)[c]
WPM	1 (1,2)[a]	858 (354,1856)[b]
FSM	1 (1,2)[a]	634 (400,1072)[a]
P(0.05)	0.073	0.110

Different letters show significant (Mann–Whitney U-test, p < 0·05) differences between treatments, a < b < c. *Co* Control, *BPM* black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch

treatments varied from 632 to 931. The minimum and maximum numbers of grains per crop were observed in the control and black plastic mulch, respectively. The maximum number of cobs per crop was observed in the black plastic mulch.

The maximum number of grains per crop was observed in black plastic mulch (931) followed by white plastic mulch (858), straw mulch (634), and the control (632). In line with this finding, Wang et al. [36] also reported that transparent, black, and straw mulches have no significant effect on the number of cobs per crop. The total number of grains per crop was not also significantly affected by mulching treatments [24]. As Kara and Atar [37] pointed out, plastic mulch significantly increases the total number of ears and grains of sweet corn per hectare followed by no much and straw mulch. In addition to this, plastic mulch increases the total number of ears and grains per crop by 12% relative to no mulch or control [9]. As Rani et al. [8] and Kamar et al. [38] found out, the number of grains per cob is higher in mulched plant growth than without mulch. On the other hand, Zhang et al. [14] and Kumar [39] found that straw mulch significantly increased the number of grains per cob compared to no mulching. The number of grains per cob were maximum in hand weeding mulch (278), followed by black plastic mulch (269), white plastic and weeds mulch (251), and living mulch (246) [23].

3.4.2 Cob length and cob diameter

The effect of different mulches on cob length and cob diameter, which were measured after 3 days from the harvest time is shown in Fig. 10. The diameters of the cob were measured at the head, middle and tail of the cob. The mean values of these three measurements were taken as the mean cob diameter of a crop.

The result from this study showed that there is a significant ($p < 0.05$) effect of treatments on cob length per crop. The mean cob length varied from 12.21 to 17.44 cm (Fig. 10). The minimum and maximum cob lengths were observed in the control and white plastic mulch, respectively. On the other hand, there was no significant effect of treatments on cob diameter.

The white plastic mulch (17.44 cm) had the longest mean cob length, followed by the black plastic mulch (17.40 cm), the straw mulch (13.22 cm), and the control (12.21 cm). Despite the fact that there was no statistically significant change in diameter, the observed mean cob diameter under various mulch types ranged from 3.39 cm (control) to 3.96 cm (white plastic mulch). Thus, white plastic mulch (3.96 cm) had the highest mean cob diameter, followed by black plastic mulch (3.95 cm), straw mulch (3.79 cm), and the control (3.39 cm). Cob length and cob diameter differences between inorganic

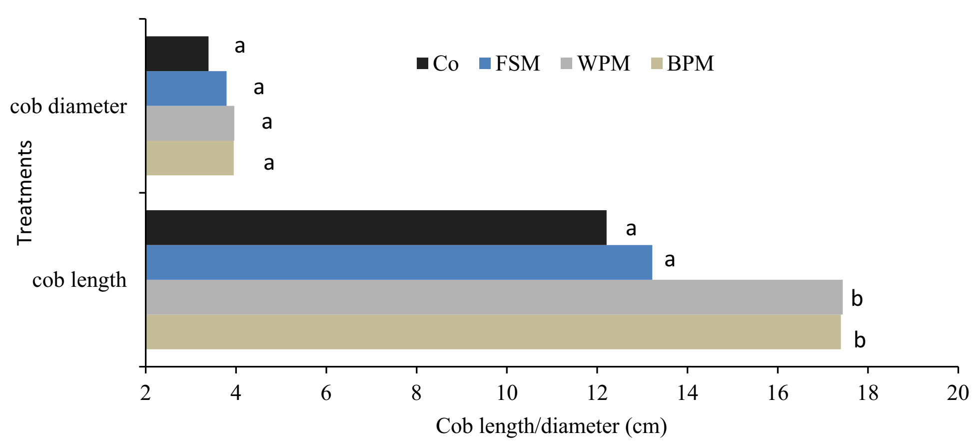


Fig. 10 Effect of different mulches on cob length and diameter (cm). Different letters show significant (Tukey-test, p < 0·05) differences between treatments, a < b. *Co* Control, *BPM* Black plastic mulch, *WPM* White plastic mulch, *FSM* Flax straw mulch

mulches were negligible. However, organic mulches have a role in the increment of both cob length and cob diameter, inorganic mulch produced higher cob length and cob diameter compared to the control (no mulch).

Meskelu et al. [34] and Kara and Atar [37] found that cob length (16.6 and 18.4 cm) and cob diameter (4.5 and 4.52 cm) were higher in plastic mulch than in straw mulch and no mulch. In other studies, straw mulch significantly increased cob length [39] and cob diameter [14] compared to the control (no mulch). Contrary to this result, Kara and Atar [36] found that transparent, black and straw mulches did not have any significant effect on cob length compared to the control.

3.4.3 Weight of 1000-grains

The effect of different mulches on the weight of maize (1000 grains) which was measured 7 days after harvest is summarized in Table 7. There was a significant ($p < 0.05$) effect of treatments on the weight of 1000 grains. The observed mean grain weight varied from 163 to 188.37 g. The minimum and maximum weights of 1000 grains were observed in the control and white plastic mulch, respectively. The maximum mean weights of 1000 grains were found in white plastic mulch followed by black plastic mulch, straw mulch and the control (Table 7). The maximum weight of 1000 grains occurred in plastic mulches, because inorganic mulch conserves high moisture content, avoids weeding, and reduces water and nutrient consumption of weeds relative to organic mulches and the control. As result, higher weight of 1000 grains was observed in the inorganic treatments compared to the other treatments.

Similar to this study, Wang et al. [36] also found a maximum weight of 1000 grains in transparent plastic mulch (34.39 g) followed by black pastic mulch (34 g), control (33.5 g), and straw mulch (32.4 g). Xu et al. [9] and Kamar et al. [38] also reported similar results, with plastic mulch having a higher weight of 1000 grains of maize compared to no mulching. Rummana et al. [40] also indicated that the weight of 1000 grains of wheat was maximum in black plastic mulch (43.59 g), followed by rice straw mulch (42.15 g), and a control (39.48 g). Other researchers [8, 14, 39] have also observed a significant effect of straw mulch on the weight of 1000-grains compared to the control. In addition to this, Gul et al. [23] reported that the weight of 1000 grains was maximum in hand weeding (187 g), followed by black plastic mulch (184 g), white plastic mulch (175 g), living mulch (174 g) and weed mulch (172 g).

3.4.4 Total grain yield and biomass

The effect of different mulches on the total grain yield and biomass of maize is shown in Table 7. Maize grain yield and biomass were measured 7 and 10 days after harvest, respectively.

The outcome showed that treatments had a significant ($p < 0.05$) impact on the overall grain yield and biomass. Both the white and black plastic mulches greatly outperformed the control in terms of grain yield and biomass. However, compared to the control, flax straw mulch had no discernible impact on grain yield or biomass. The range of grain yield per hectare was 1313.4 to 2418.16 kg. The mean biomass yield also ranged from 5375 to 7781.25 kg ha^{-1}. White plastic mulch (2418.16 kg ha^{-1}) had the highest overall yields of maize, followed by black plastic mulch (1651.56 kg ha^{-1}), control (1363.36 kg ha^{-1}) and straw mulch (1313.4 kg ha^{-1}). On the other hand, black plastic mulch had the highest biomass (7781 kg ha^{-1}), followed by white plastic mulch (6251 kg ha^{-1}), straw mulch (5979.17 kg ha^{-1}), and the control (5375 kg ha^{-1}). The maximum values of grain yield and biomass were produced in the inorganic mulches. Lower values of grain yield and biomass were observed in the control and organic mulches. The differences in grain yield and biomass between flax straw mulch and the control were non-significant (Table 7). However, the differences in grain yield and biomass between inorganic and organic mulches were significant.

Table 7 Effect of mulch on total grain yield, biomass, water productivity (WP) and weight of 1000-grains (n = 3)

Treatment	Grain yield (kg ha^{-1}), median (min, max)	Biomass (kg ha^{-1}), (mean ± SD)	WP (kg m^{-3}), median (min, max)	Weight of 1000 grains (g), mean ± SD
Co	1363.36(1116.96,1470.53)^a	5375.00 ± 434.14^a	1.7 (1.39,1.84)^a	163.00 ± 4.36^a
BPM	1651.56(1633.57,2522.95)^b	7781.25 ± 298.11^c	3.19 (16,4.88)^b	172.67 ± 5.03^{ab}
WPM	2418.16(1565.95,2578.11)^c	6251.00 ± 788.71^b	5.17 (3.35,5.51)^c	188.37 ± 13.34^b
FSM	1313.4(1278.89,1434.4)^a	5979.17 ± 893.41^a	2.24 (2.18,2.45)^a	165.00 ± 3^a
P (0.05)	0.040	0.000	*0.019*	0.013

Different letters show significant (Mann–Whitney U-test, $p < 0.05$) differences between treatments, a < b < c. *Co* Control, *BPM* black plastic mulch, *WPM* white plastic mulch, *FSM* flax straw mulch

In line with this finding, total grain yield was maximum in transparent plastic mulch by 11.4%, from black plastic mulch, 13.4% from control and straw mulch gave the minimum yield [36]. Similarly, Li et al. [41] have confirmed that total maize yield was higher in plastic mulch by 24.3%, and straw mulch by 16% compared to the control. Another finding, Lin et al. [28], also point out that, the total maize yield was higher in plastic mulch by 28.3%, and in gravel mulch by 17.1% compared to the control. Shaikh and Fouda [42] and Gao et al. [43] also reported the highest grain yield in white plastic mulch, followed by yellow, black, straw mulches, and a control. Other studies also indicated that total maize grain yield [44], maize biomass were maximum in black plastic mulch, followed by white plastic mulch [45, 46]. Unlike this study, other researchers have indicated that straw mulch significantly increased maize grain yield and biomass compared to the control [27, 33, 39, 47, 48].

3.5 Water productivity (WP)

WP depends on the total amount of water applied to the crop and the total grain yield. There was a significant ($p < 0.05$) effect of treatments on WP as shown in Table 7. WP for the treatments varied from 1.7 to 5.17 kg m^{-3}. The minimum and maximum WPs were observed in the control and white plastic mulch, respectively. White plastic mulch (5.17 kg m^{-3}) had the highest WP, followed by black plastic mulch (3.19 kg m^{-3}), straw mulch (2.24 kg m^{-3}), and the control (1.7 kg m^{-3}). However, the inorganic mulches (BPM and WPM) did not result in a significant difference in WP between them. In general, inorganic mulches produced higher WP values compared to organic mulches and no mulching. Likewise, other researchers [12, 36, 42, 49] have found higher WP in white plastic mulch, followed by black polyethylene plastic mulch and straw mulch. Similarly, maize WP was higher in plastic mulches compared to straw mulch and no mulch [34, 41, 43]. Overall, mulching has a considerable impact on WP compared to no mulching, as demonstrated by this study and other related studies [8, 38, 50]. In another study, Ramalan et al. [13] observed higher irrigation WP in teff straw mulch than white plastic and black plastic mulches and reduced irrigation water by about 400 mm every season. The result by Ramalan et al. [13] is in contrast to the findings of this study and other related studies described above. On the other hand, Berihun [51] has shown that crops under black plastic mulch utilize the least amount of water throughout the season, resulting in a greater WP (15 kg m^{-3}) than straw (12.33 kg m^{-3}) and without mulch (9.28 kg m^{-3}). El-Kholy and Eid [52] also showed similar results, with higher WP values in black polyethylene plastic mulch, banana leaves, and rice straw mulches, compared to the control. A study by du Plessis [53] revealed that the WP of a maize crop with a total yield of 3152 kg ha^{-1} varied between 0.9 to 0.7 kg m^{-3} with 250 Liter seasonal water consumption without stress. Based on the economic analyses, the economic net return and benefit cost ratio was maximum in the white plastic mulch (1459 USD/ha) followed by the black plastic mulch (1119.63 USD/ha), flax straw mulch (847.09 USD/ha) and the control (796.24 USD/ha). Similarly, the benefit cost ratio was maximum in the white plastic mulch (1.98), followed by the black plastic mulch (1.75), flax straw mulch (1.55), and the control (1.53).

4 Conclusion

This study investigated the effect of organic and inorganic mulching options on water productivity (WP), maize yield and yield components in semi-arid northern Ethiopia. Overall, this study revealed that mulching options such as white plastic, black plastic, and flax straw have positive effects on soil moisture content (SMC), WP, yield and yield components of maize. Specifically, white plastic mulch significantly improved SMC compared to no mulching. On the other hand, SMC did not significantly increase with the application of black plastic and flax straw mulches, compared to no mulching.

Maize grain yield and biomass were significantly higher in the white and black plastic mulches than in the flax straw mulch and the control. Furthermore, flax straw mulch did not significantly increase neither of maize grain yield or biomass compared to no mulching. WP was significantly increased by white and black plastic mulches compared to no mulching option, unlike the flax straw mulch which had no significant effect on WP. This research is limited to the maize crop only, hence, further research is necessary to explore the effect of different organic and inorganic mulching options on WP and yield in other crops other than maize.

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Statements and declaration The study evaluated the effect of organic and inorganic mulching options in improving soil moisture content, water productivity, maize yield and yield components with an irrigated experiment in the semi-arid northern Ethiopia. We assure that this work is an authentic and has not been published or accepted for publication, nor is being considered for publication elsewhere, either in whole or substantial part.

Author contributions All authors contributed to the study conceptualization (TY); design and methodology (TY, BG, GA), material preparation, data collection, analysis and original draft preparation (TY); review and editing (BG, GA). All authors read and approved the final version of the manuscript.

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Data availability The data used for this research can be obtained from the first author upon request (tamiyisfa@gmail.com).

Declarations

Competing interests The authors declare no competing interests.

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