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Influence of polyethylene film colour and soil solarisation duration on weed dynamics and performance of hybrid maize (*Zea mays* L.)

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Abstract A two-year assessment of polyethylene film colour (PFC) and soil solarisation duration (SSD) on hybrid maize performance and weed flora dynamics was conducted in Calabar, Nigeria. Result showed that PFC, SSD and PFC × SSD were significantly differed on most attributes in both years. PFC (transparent white, W) enhanced plant height, stem girth, number of seeds per pod, grain yield and weed density in 2017. Growth and yield of the hybrid maize were enhanced with increasing SSD, except for number of leaves per plant. Hybrid maize with treatment interaction, W × six weeks soil solarisation (S_6), produced the highest ($p \leq 0.05$) grain yield (4.72 t ha^{-1}), while W × no solarisation (S_0) produced the lowest grain yields (1.73 t ha^{-1}). Weed density, weed dry matter, and weed abundance had inversed relationships with SSD irrespective of the PFC. Treatment W × S_6 gave the best weed reduction: 75% broadleaves (in 2016), 33.33% broadleaves and 33.33% grasses (in 2017). It was followed by PFC (green, G) × S_6, with 41.47% broadleaves and 50% grasses reduction in 2016 and 2017, respectively. Overall, W × S_6 enhanced maize productivity and maximally reduced weed infestation. Thus, W × S_6 was recommended for maize farmers in Calabar and its environs with similar agroecological attributes.

Keywords: Grain yield, Maize, Polyethylene film colour, Soil solarisation duration, Weed flora dynamics

Introduction

Maize (*Zea mays* L.) is ranked the most abundantly produced cereal in the world (IITA 2022), and together with sugarcane, wheat and rice, accounts for 50% of the world's agricultural production (IndexMundi, 2021). Maize is produced in all the continents of the world except Antarctica (IITA 2022), with the United States of America (USA) as the world largest producer, followed by

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China, and Brazil. Maize is considered a food security crop especially in Africa and it has a wide variety of uses: animal feed, vegetable oil, starch, alcoholic beverages, and bio-fuel (Ranum *et al.*, 2014). Nigeria is the second largest producer of maize in Africa after South Africa. Maize is being grown across all the agroecological zones in Nigeria, predominantly by small holder farmers, who use low technology and inadequate inputs, resulting in low yields. Nigeria's average maize grain yield remains very low (1.59 t ha^{-1}) (FAO, 2021).

Weed interference has been identified as a major biotic factor limiting maize production and productivity (Nwagwu *et al.*, 2020), with an average yield loss of 38% in Africa, and 29% globally (Nwagwu *et al*., 2020; Tahir, 2014; Takim, 2012). Crop yield is a function of several variables such as genotype, environment, and crop management (Abagisa, 2021); ineffective weed management can hamper the actualization of crop yield potential, e.g., through allelopathy (Zohaib *et al.*, 2016), even with improved varieties and adequate inputs. The type, density and biomass of weed flora in a given crop field are major indices that determine crop yield losses due to weeds (Al-Solimani *et al.*, 2015; Das and Yaduraju, 2008; Nkoa *et al*., 2015). The drudgery, high labour demand and high cost needed for repeated operations associated with hand weeding have made this most commonly employed weed control practice in West Africa increasingly undesirable, especially in large-scale crop farms. Conversely, environmental and health risks (Scavo *et al*., 2019) unavailability, high cost and inadequate skill militate against herbicide use among local farmers. Alternative physical weed management technologies are highly desirable, such as soil solarisation, which can effectively enhance crop yield while minimizing the negative consequences of herbicides (and other weed control practices) (Elmore *et al.*, 1997; Hasing, 2002).

Soil solarisation is a technique of disinfesting the soil of inocula, pests, and weeds through passive solar heating using polyethylene films (Katan, 1981; Stapleton 2000). This technique has been successfully used to enhance crop growth and yield, including African spinach (Yahaya *et al.*, 2021), carrot (Frillman, 2019), legumes (Linke *et al.*, 1991), lettuce (Al-Solimani *et al.*, 2015; Candido *et al.*, 2011; Ijoyah and Koutatouka, 2009), tomato (Abu-Gharbieh *et al.*, 1991; Alshammari, 2017), eggplant (Alshammari, 2017), rice (Neogi *et al.*, 2017), and maize (Ahmad *et al.*, 1996; Marenco and Lustossa, 2000; Saloum and Almahasneh, 2015). Reported yield increases were attained through effective pathogen and weed control due to solarisation, although the efficacy differed among weed species. It has been reported that solarisation mostly controlled annual weeds (e.g., *Ageratum* spp., *Amaranthus* spp., barnyard grass, cogon grass, *Digitaria* spp., *Portulaca* spp., *Setaria* spp., *Plantago*spp., *Chenopodium murale, Vicia spp*.) and, some perennial weeds (e.g., *Cynodon dactylon*), while noxious perennial weeds (e.g., *Cyperus* spp. and *Convolvulus arvensis*) were resistant to solarisation (Benlloglu *et al.*, 2005; Linke *et al.*, 1991).

The colour of polyethylene films and duration of solarisation are important contributors to the effectiveness of soil solarisation in enhancing crop yield and weed control, with variable results. Common colours of plastic being used for crop farming currently include, black, white, green, brown, red, silver, blue (Amare and Desta, 2021), and transparent (Yahaya *et al.*, 2021). Transparent films enhanced crop yield more than either black or white film (Abu-Gharbieh *et al.*, 1991; Al-Solimani *et al.*, 2015; Yahaya *et al.*, 2021). Film colours had similar effects on crop performance (Hasing, 2002). Polyethylene film colour has also variable effects on weed density and weed dry matter (Al-Solimani *et al.*, 2015). A pre-plant solarisation period of 45 days has been recommended for maize (Saloum and Almahasneh, 2015), but 30 to 35 days solarisation effectively controlled weeds in maize field (Sharma and Kumar, 2013**).** Whereas weed density was similar among 2-, 4-, and 6-week soil solarisation durations (Seman-Varner and McSorley, 2012), soil solarisation for 20 days was ineffective in weed control (Gul *et al.*, 2013). Duration of 4 to 8 weeks tarping was necessary to control noxious sedges such *Cyperus* spp (Kapoor, 2020; Seman-Varner and McSorley, 2012). The objective was to assess the effectiveness of three colours of polyethylene film (blue, green and transparent white), and four durations of soil solarisation (no solarisation, 2-, 4- and 6-weeks) for weed management in rainfed hybrid maize grown in the tropical humid rainforest agroecology of Calabar, Cross River State, Nigeria.

Materials and methods

Study site, experimental design and field layout

The study was conducted between March 1 and June 30 of 2016 and 2017. The experimental site was at the University of Calabar Teaching and Research Farm, Calabar, Cross River State, Nigeria. Average minimum and maximum data on temperature, rainfall, relative humidity, sun hours, sun days and ultraviolet index during the study period was obtained and documented. The site had a secondary vegetation comprising of annual and perennial weeds. These were manually slashed and cleared with machete. The debris were packed and removed. The experiment consisted of two factors at different levels. The first factor was polyethylene film colours (PFC) and the second factor was soil solarisation duration (SSD). PFC had three levels represented by the different film colour types: black (B), green (G), transparent white (W). SSD had four levels represented by the number of weeks: 0 (S_0), 2 (S_2), 4 (S_4), and 6 (S_6). These twelve treatment combinations from PFC × SSD were laid out in a randomized complete block design (RCBD) replicated three times.

The soil was tilled and raised beds (3 m × 1.5 m × 0.3 m) with fine tilth and levelled tops were made. A total of 36 raised beds were made to accommodate all the treatment combinations. Each block had 12 beds with the treatments randomly assigned using a table of random numbers. These beds were separated by 1 m alley within and between blocks. Polyethylene films (100 µ thickness) with the respective colours were cut to sizes adequate to completely cover the raised beds. Beds with treatment combinations that had S_6, S_4 and S_2 were covered (for solarisation) at six, four and two weeks prior to the scheduled planting date, respectively. Beds that had treatment combinations with S_0 were not covered with polyethylene films (no solarisation). The edges of the films overlapping the sides of the completely covered beds were held in place by soil clods to about 10 cm high. The solarisation process took place from March 1 to April 12, 2016 and 2017. These were done to synchronise with a uniform planting date which was the April 12 in both years. On the sixth week, the polyethylene films were removed and the non-solarised plots remained as the control plot.

Seeds of an early maturing hybrid maize variety, Oba Super 2, used in the study were obtained from the seed unit of the Cross River Agricultural Development Programme (CRADP), Calabar, Cross River State, Nigeria. Two seeds per hole were sown at an intra- and inter-row spacing of 75 cm × 25 cm. Thinning to one stand per hill was done at two weeks after sowing (WAS). Each bed had 55stands of plants.

Data collection

At 4 and 8 WAS, plant height, stem girth, number of leaves per plant, and leaf area data were collected from 10 tagged plants in each net plot (225 cm × 25 cm) earmarked within the bed. Other data collected were: days to 50% flowering, number of seeds per cob and grain yield estimates (t ha^{-1}).

Weed assessment was done at 3, 6, and 9 WAS. Weed density was determined as described by Nwagwu *et al.* (2020). Individual weed species were identified and classified according to the method of Akobundu *et al.* (2016). Weed flora absolute abundance (Wf_a) and relative abundance (Wf_{ra}) were determined using formulae proffered by Mueller-Dombois and Ellenberg (1974):

$$Wf_a = \frac{\text{Total number of individuals species in all quadrats}}{\text{Total number of quadrats in which the species occurred}} \quad (1)$$

$$Wf_{ra} = \frac{\text{Individual species abundance}}{\text{Total species abundances}} \times \frac{100}{1} \quad (2)$$

Individual samples of harvested weeds for each of the treatment combinations from the three blocks were bulked into one representative sample per treatment combination (i.e., 12 samples) and oven dried at 70 °C to a constant weight to determine the dry matter content (kg ha^{-1}).

Statistical analysis

Effect of PFC and SSD on the growth and yield of maize and weed density were evaluated by two-way analyses of variance (ANOVA) conducted at alpha level (α) = 0.05. The ANOVA analyses utilised randomised complete block model using GenStat 18^{th} Edition (VSN International 2015). PFCs and SSDs were incorporated into the model as fixed effects to evaluate the main and interaction effects on the maize and weed variables assessed. Significant main and interaction effects were further analysed to conduct Fisher's least significant difference means separation test.

Results

Weather conditions and soil properties at the experimental site

The weather variations at the experimental site during the period of the study (February – June in 2016 and 2017) are presented in Table 1. In 2016 the maximum and minimum temperatures ranged from 30-36 ℃ and 24-26 ℃ respectively. The total rain days were 82 days with a total of 1,357.29 mm of rainfall. From February to June, cloud cover increased with relative humidity alongside air pressure. The average sun hours, sun days and ultraviolet index was 323.6 h, 13.8, 6.2 respectively. In 2017, whereas the average monthly maximum temperature remained the same as in 2016 in February and March, there was a slight increase in April to June. However, the minimum temperature remained the same. The total rain days and rainfall amount were 73 days and 975.11 mm, lower than 2016. Except for relative humidity ($p = 0.009$) and cloud cover ($p = 0.048$), paired studentised t-test showed no significant ($p > 0.05$) difference in other weather conditions in 2016 and 2017 at the experimental site during the study period. The soil chemical parameters where lower at post-harvest in both years, except for organic carbon, exchangeable acidity and effective cation exchange capacity which were higher at post-harvest (Table 2). The soil particle distribution placed the soil in a loamy sand texture category. Exchangeable sodium remained unchanged.

Table 1. Weather conditions at the experimental site during the study

Weather Variable	2016					2017					Mean		
	February	**March**	**April**	**May**	**June**	**February**	**March**	**April**	**May**	**June**	**2016**	**2017**	**t-test**
Temperature (℃)													
Maximum	36	33	32	31	30	36	33	34	33	31	32.4	33.4	NS
Minimum	25	26	26	25	24	25	26	26	25	24	25.2	25.2	NS
Rain (mm)	112.40	434.54	201.60	234.33	374.42	41.91	191.10	148.30	199.60	394.20	271.458	195.022	NS
Rain days	6	23	17	18	18	4	22	13	14	20	16.4	14.6	NS
Rel. humidity (%)	72	78	79	81	84	69	75	74	77	83	78.8	75.6	0.009
Cloud (%)	39	42	48	53	63	36	43	42	49	58	49	45.6	0.048
Pressure (mb)	1010.6	1010.8	1010	1012.4	1014.2	1010.3	1009.9	1010.2	1011.7	1012.5	1011.6	1010.92	NS
Sun hours (h)	326	354	336	310	292	317	339	340	325	305	323.6	325.2	NS
Sun days	23	8	13	13	12	24	9	17	17	10	13.8	15.4	NS
UV index	6	7	6	6	6	6	7	6	6	6	6.2	6.2	NS

NS = Not significant at 95% confidence level.

Table 2. Soil physical and chemical properties before and after the experiment

Property	2016		2017	
	Pre-plant	**Post-harvest**	**Pre-plant**	**Post-harvest**
Sand (g kg^{-1})	811	808	793	793
Silt (g kg^{-1})	131.5	133.3	150	130
Clay (g kg^{-1})	57.5	58.7	57	77
Texture	Loamy Sand	Loamy Sand	Loamy Sand	Loamy Sand
pH (H_2O)	5.67	5.18	5.55	5.23
Total nitrogen (%)	0.08	0.06	0.09	0.07
Available phosphorus (mg kg^{-1})	27.57	21.5	24.25	24
Organic carbon (%)	1.17	1.89	1.21	1.84
Exchangeable potassium (cmol kg^{-1})	0.2	0.07	0.19	0.08
Exchangeable calcium (cmol kg^{-1})	6.86	6.63	6.4	6.2
Exchangeable magnesium (cmol kg^{-1})	1.88	1.74	1.93	1.68
Exchangeable sodium (cmol kg^{-1})	0.07	0.07	0.06	0.06
Exchange acidity (H^+)	0.25	0.82	0.34	0.97
Effective cation exchange capacity (ECEC)	9.26	9.33	8.92	8.79
Base saturation (%)	97.3	91.21	96.18	88.96

Growth and yield attributes of hybrid maize under PFC × SSD interactions

The interaction effects, transparent white (W) × soil solarisation duration of six weeks (S_6) produced the tallest plants which similar to green (G) polyethylene film colour (PFC) × S_6, and black (B) PFC × S_6, whereas, all PFC × no solarisation (S_o) interactions at 4 and 8 WAS produced the shortest plants which similar to all PFC × soil solarisation duration of two weeks (S_2) interactions (Figures 1 and 2). The W × S_6 interaction produced the thickest stems at both 4 and 8 WAS in both years (Figures 3 and 4). All PFC × S_0 and PFC × S_6 interactions produced thinner and thicker maize stems, respectively.

PFCs × SSDs interaction effects on NL were significant ($p \leq 0.05$) at 4 and 8 WAS only in the first year (2016). Although W × S_6 interaction at 4 and 8 WAS produced hybrid maize plants with significantly ($p \leq 0.05$) higher NL in 2016, there was no significant difference among W× S_6 and other PFC × S_0 interactions effect in 2017 and annual mean at 4 and 8 WAS (Figures 5 and 6). Interactions effect showed that W × S_6 produced maize hybrid plants with the highest LA at 4 and 8 WAS in 2016 (Figure 7) and 2017 (Figure 8). Overall, influence of PFCs × SSDs interactions on yearly LA and average LA increases of hybrid maize were significant ($p \leq 0.05$). All PFC × S_6 interactions produced the broadest leaves, whereas the narrowest leaves were obtained among PFC × S_0 interactions effect in both years.

PFC × SSD interaction significantly ($p \leq 0.05$) influenced the days to 50% flowering (D50F), number of seeds per cob (NSC) and grain yield (GY) of hybrid maize (Oba Super 2) in a two-year field trial (2016 and 2017) (Figures 9-11). The D50F for W × S_6, G × S_6 and B × S_6 were not significantly different ($p > 0.05$). Meanwhile, all PFC × S_0 interaction effects increased the D50F for the hybrid maize across the years.

In considering the PFC × SSD interaction effect on NSC (Figure 10), hybrid maize under W × S_6 produced significantly ($p \leq 0.05$) the highest NSC followed by G × S_6 and B × S_6. All PFC × S_0 interactions produced the lowest NSC across the years. The PFC × SSD interactions effect revealed that the hybrid maize under PFC × S_6 produced significantly ($p \leq 0.05$) the highest GY ranging from 4.00 to 4.72 tha^{-1} in 2016 and 3.85-4.63 t ha^{-1} in 2017. PFC × S_0 had the lowest GY in 2016 (1.80-1.89 t ha^{-1}) and 2017 (1.56-1.74 t ha^{-1}). Overall, hybrid maize under W × S_6 had the highest mean annual grain yield of 4.72 t ha^{-1} which was significantly different from all other treatment combinations.

Weed density and weed dry matter under PFC × SSD interactions

Of the three types of PFCs, the W type PFC had the highest effect on weed density (WD) in both years. As the SSD increased, weed density (Figure 12) and weed dry matter (WDM) (Figure 13) decreased ($p \leq 0.05$). Apart from the G × S_6 interaction effect in 2017, the W × S_6 interaction had the greatest impact on the WD reduction compared with other treatment combinations. The highest WDs (i.e., lowest weed reduction) were obtained from all PFC ×S_0 interactions across the two years. Consequently, a comparable trend was followed by WDM. The lowest WDM was recorded under W × S_6, this was statistically similar to G × S_6 and B × S_6. The highest WDM came from all PFC × S_0 in both years.

Weed flora abundance and relative abundance under PFC × SSD interactions

A total of 21 weed species, from 10 plant families, comprising broadleaves (57.14%), grasses (28.57%) and sedges (14.29%) were recorded (Table 3 - 6). This comprised of 47.62% annuals and 52.38% perennials weed species. The effects of PFC and SSD on weed flora abundance (WA) and relative abundance (WRA) in 2016 and 2017 are also presented. The WA decreased with increase in SSD, with highest WA values recorded in S_0 across PFCs and years. Overall, WA values for broadleaves, grasses and sedges followed the order $S_6 \leq S_4 \leq S_2 \leq S_0$. In most broadleaves, complete extinction occurred under PFC × S_6 treatment combinations. In W × S_6, there was 75% broadleaves (*A. conyzoides*, *A. africaca*, *B. diffusa*, *E. heterophylla*, *E. hirta*, *E. sonchifolia*, *S. acuta*, *S. rhombo* and *T. procumbens*) extinction in 2016 (Figure 14). In 2017, there was 33.33% and 23.33% broadleaves (*A. conyzoides*, *E. sonchifolia*, *T. procumbens*, *S. cayennesis*) and grasses (*D. horizontalis and E. tenella*) extinction respectively (Figure 15). Under G × S_6, 41.47% broadleaves (*A. conyzoides*, *A. africaca*, *E. hirta*, *E. sonchifolia*, *S. acuta*, *T. procumbens)* and 50% grasses (*C. dactylon*, *S. barbata*, *S. longiseta*) got extinct in 2016 and 2017, respectively. However, the sedges (*Cyperus rotundus*, *Cyperus esculentus,* and *Maricus alternifolius* Vahl.) had the highest abundance (Tables 3 and 4) and relative abundance (Tables 5 and 6) across treatment combinations in 2016. Also, the relative abundance of such weeds as *C. rotundus*, *M. alternefolius* and *M. maximus* increased under all PFC × S_6.

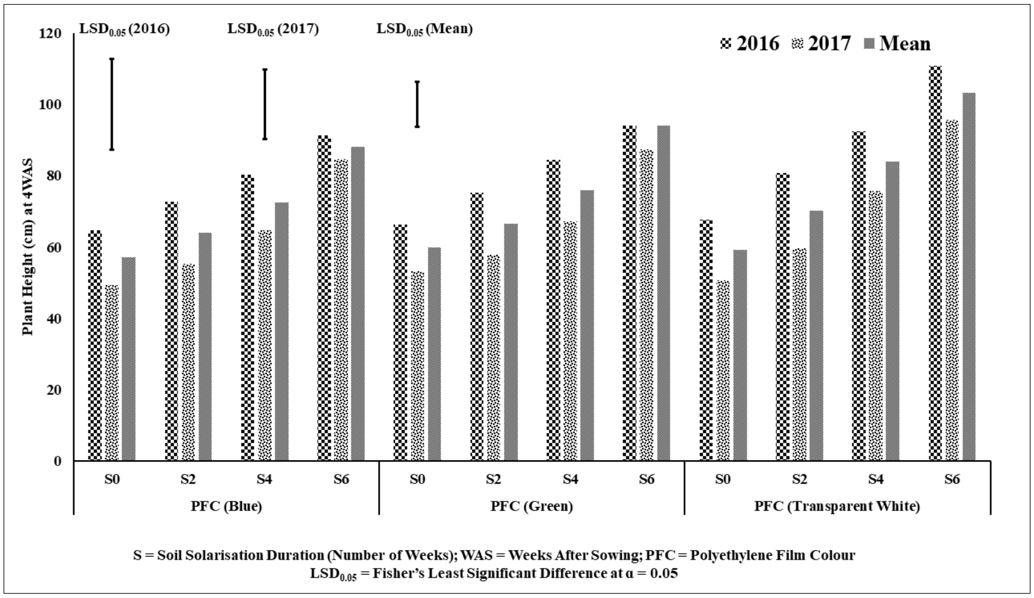

Figure 1. PFC × SSD interactions effect on plant height (cm) of hybrid maize at 4 WAS

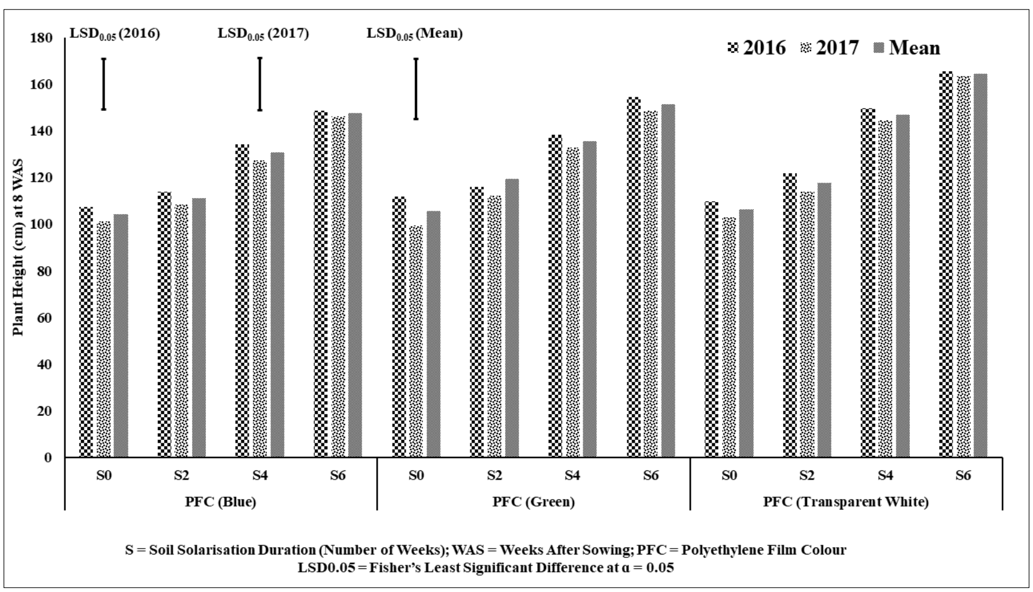

Figure 2. PFC × SSD interactions effect on plant height (cm) of hybrid maize at 8 WAS

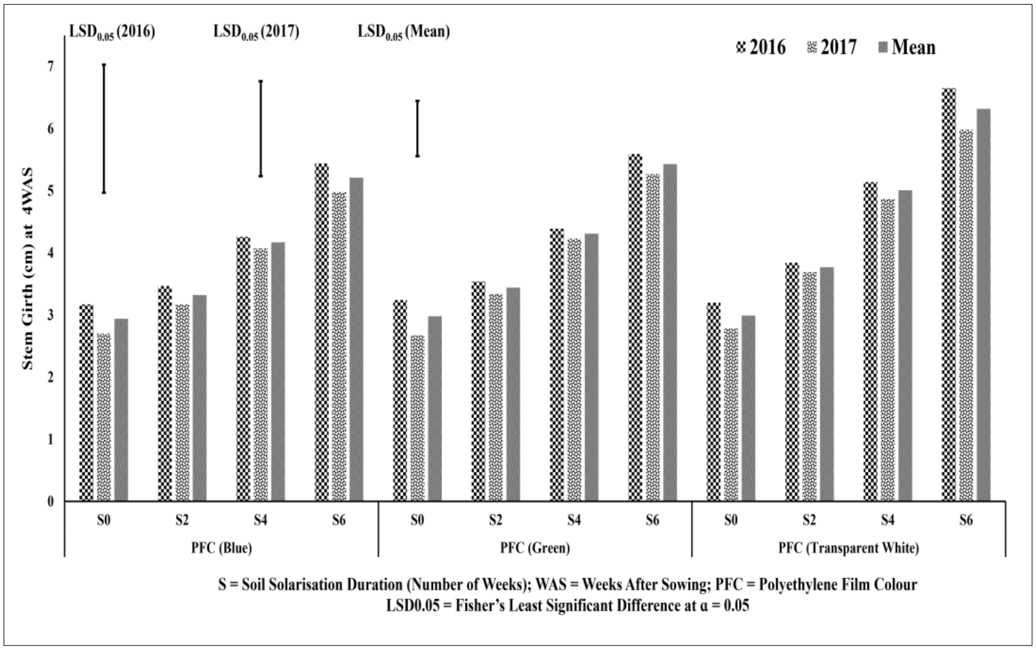

Figure 3. PFC × SSD interactions effect on stem girth (cm) of hybrid maize at 4 WAS

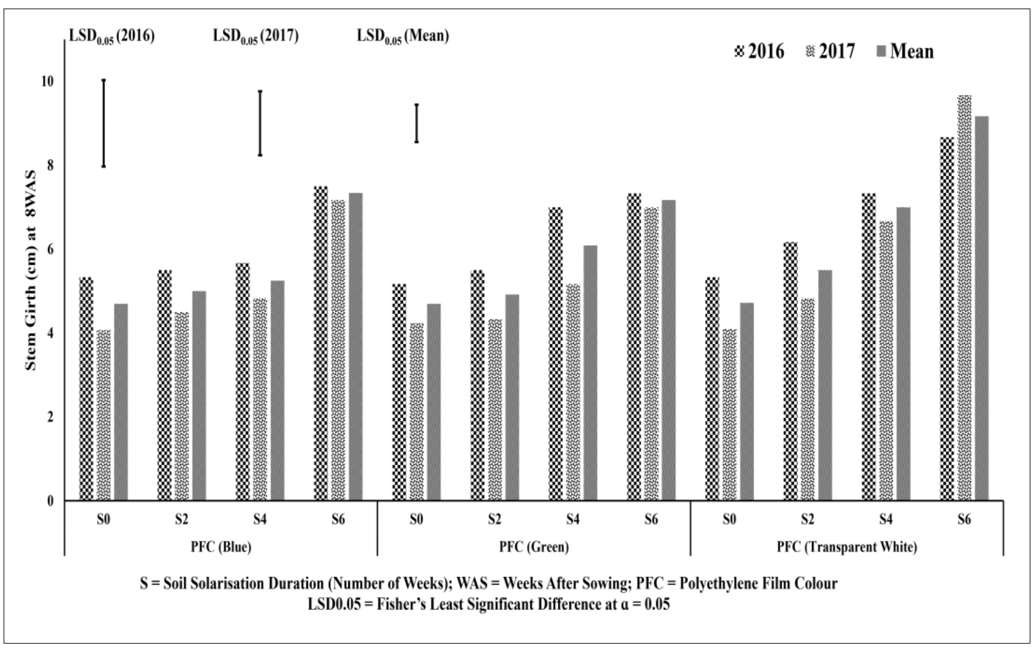

Figure 4. PFC × SSD interactions effect on stem girth (cm) of hybrid maize at 8 WAS

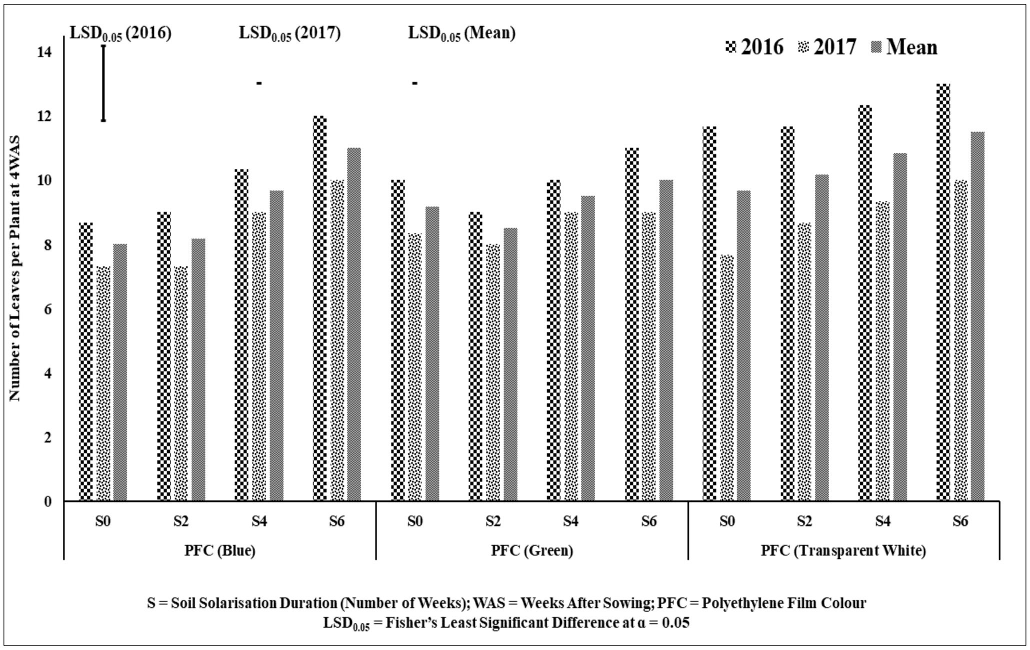

Figure 5. PFC × SSD interactions effect on number of leaves per plant of hybrid maize at 4 WAS

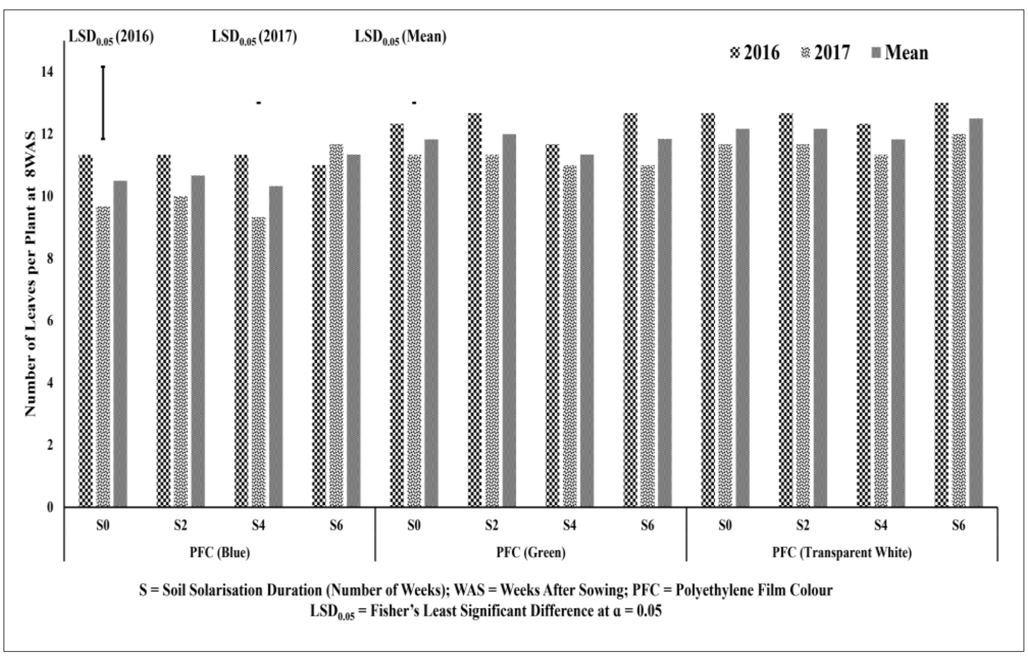

Figure 6. PFC × SSD interactions effect effect on number of leaves per plant of hybrid maize at 8 WAS

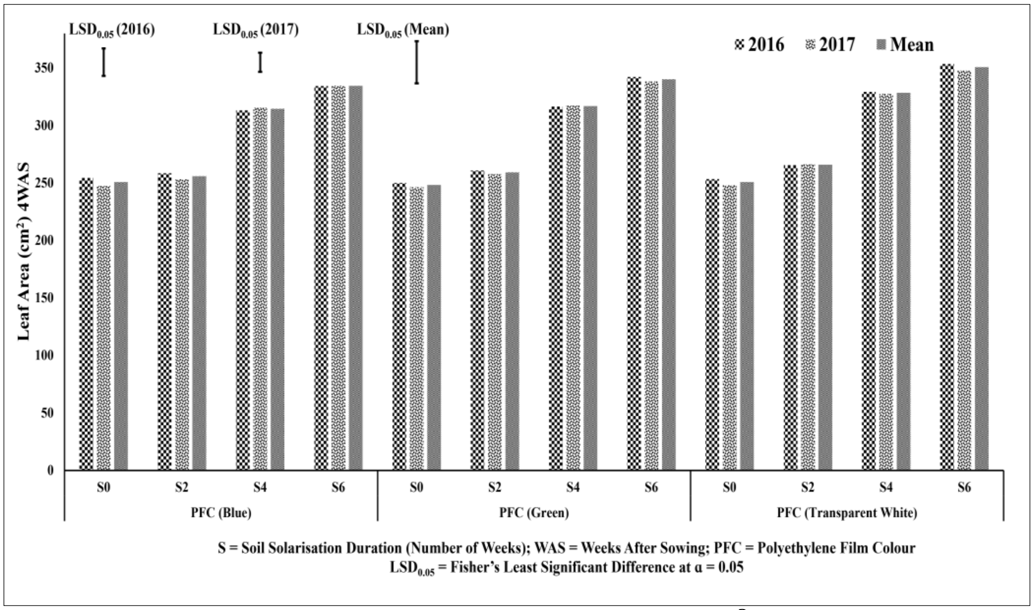

Figure 7. PFC × SSD interactions effect on leaf area (cm^2) of hybrid maize at 4 WAS

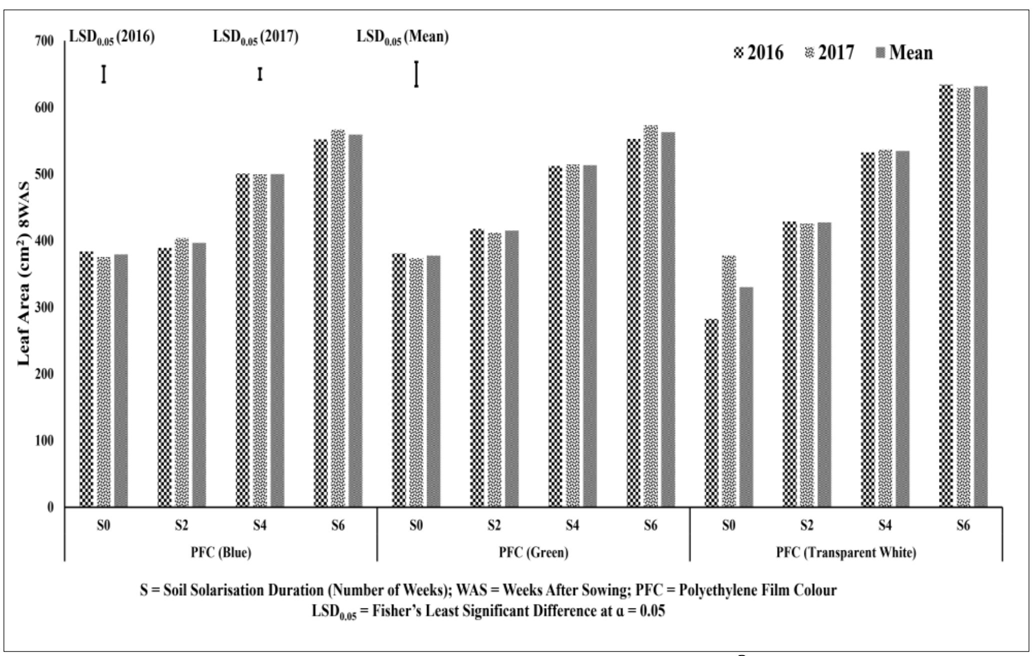

Figure 8. PFC × SSD interactions effect on leaf area (cm^2) of hybrid maize at 8 WAS

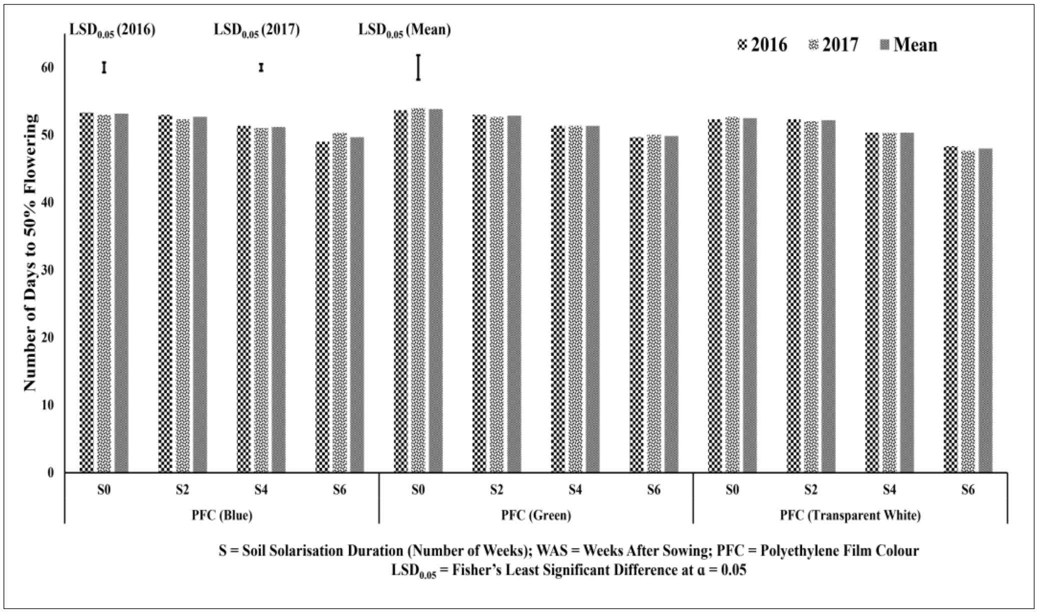

Figure 9. PFC × SSD interactions effect effect on number of days to 50% flowering of hybrid maize

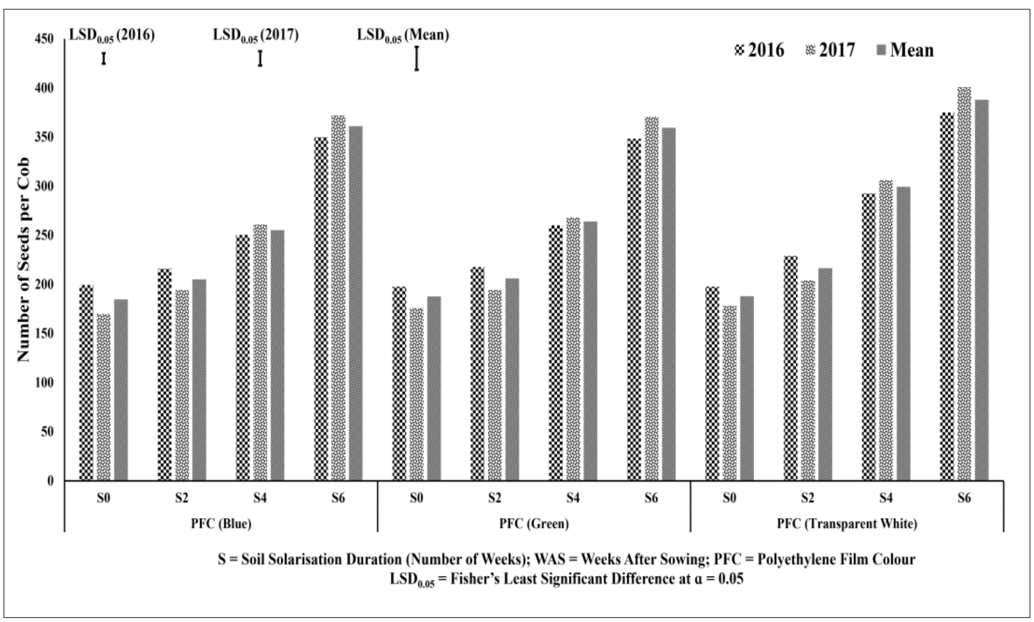

Figure 10. PFC × SSD interactions effect on number of seeds per cob of hybrid maize

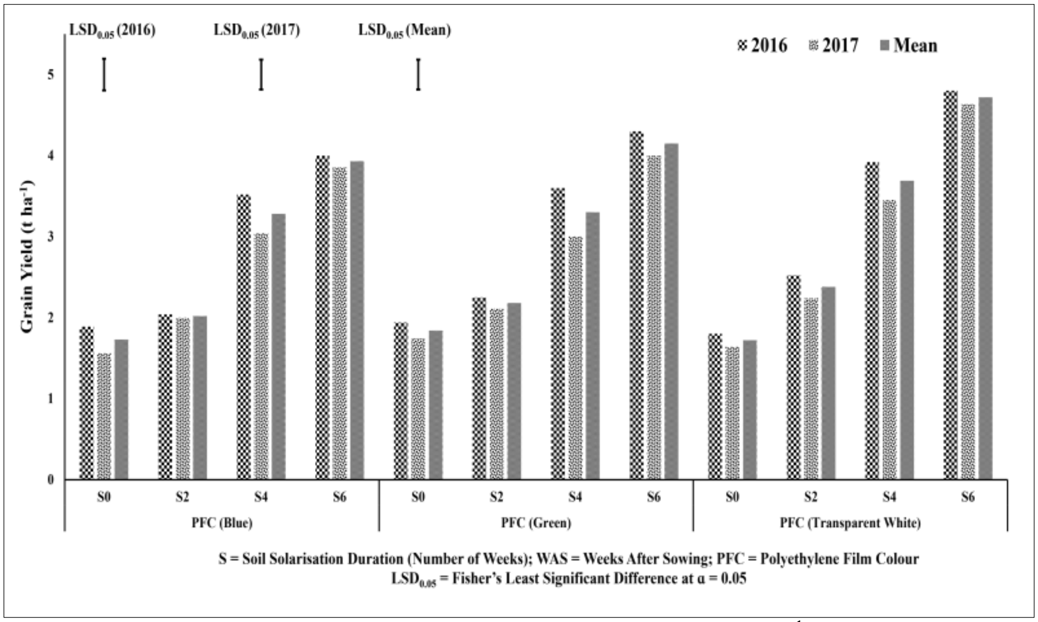

Figure 11. PFC × SSD interactions effect on grain yield (t ha^{-1}) of hybrid maize

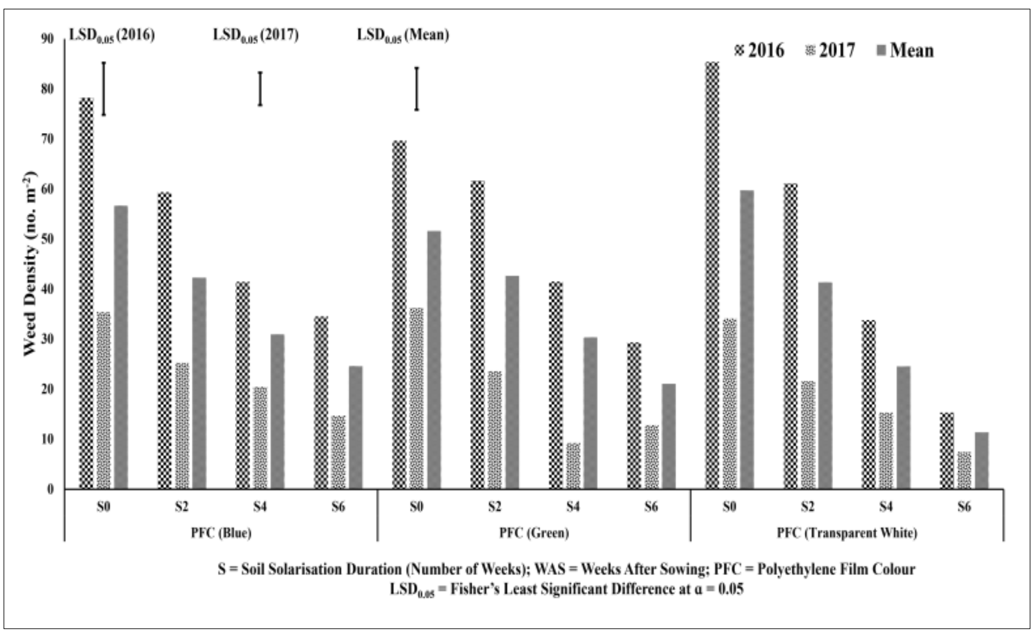

Figure 12. PFC × SSD interactions effect on weed density (no. m^{-2}) in hybrid maize field

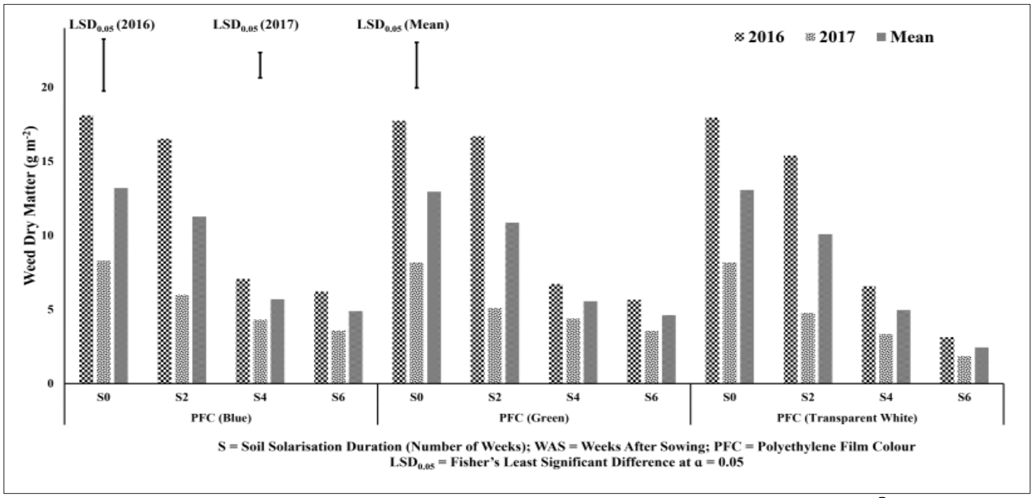

Figure 13. PFC × SSD interactions effect on weed dry matter (g m^{-2}) in hybrid maizefield

Discussion

Growth attributes

The use of transparent white polyethylene film for soil solarisation did enhance the growth performance of hybrid maize compared to black and green polyethylene films. This was attributed to higher weed suppression, lower weed density and reduction in weed dry matter (biomass). Similar finding was reported on increased height and stem width of *Amaranthus viridis* under transparent polyethylene film in comparison with black polyethylene film (Yahaya *et al.*, 2021). However, the similarity in growth attributes of maize among the three colours of films at most sampling periods suggests that each of the films had positive effect on plant growth. This finding is similar to that of Hasing (2002), who reported that clear and black polyethylene films both enhanced lettuce growth. The significant increase in maize growth performance due to solarisation in contrast to the non-solarised treatment is attributable to effective weed suppression by the solarisation treatment, and agrees with previous findings that solarisation increased growth performance of several crops such as eggplant, cucumber (Abu-Gharbieh *et al.*, 1991), tomato (Streck, 1995), lettuce (Ijoyah and Koutatouka, 2009), dry beans (Ibarra-Jiménez *et al.*, 2012), cabbage (Hamooh and Alsolaimani, 2014), and *Abelmoschus esculentus* (Kapoor, 2020). It has been reported that, in addition to weed and pest control, soil solarisation enhances soil health and soluble nutrient availability (EOS, 2021) thereby leading to increased growth response of crops (D'Addabbo *et al.*, 2010).

Table 3. Polyethylene Film Colour × Soil Solarisation Duration interactions effect on weed species diversity and flora abundance in hybrid maize field in 2016

Weed species	Family	Life cycle	PFC (B)				PFC (G)				PFC (W)			
			S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6
Broadleaves														
Ageratum conyzoides L.	As	P	14.00	11.00	10.00	3.00	13.00	13.00	8.00	1.00	16.00	12.00	6.00	0.00
Asipilia africana (Pers.) C. D. Adams.	Co	P	6.00	4.00	3.00	1.50	5.00	4.00	4.00	0.00	7.00	4.00	3.00	0.00
Boerhavia diffusa L.	Ny	P	6.00	6.00	6.00	2.00	7.00	8.00	5.00	1.00	9.00	7.00	4.00	0.00
Euphorbia heterophylla L.	Eu	A	8.00	7.00	6.00	1.00	9.00	8.00	6.00	1.50	9.00	8.00	4.00	0.00
Euphorbia hirta L.	Eu	A	10.00	7.00	6.00	1.00	8.00	8.00	5.00	0.00	9.00	7.00	5.00	0.00
Emilia sonchifolia (L.) DC.	As	A	6.00	5.00	4.00	1.00	6.00	5.00	5.00	0.00	8.00	6.00	4.00	0.00
Hpytis suaveolens (L.) Poit	La	A	3.00	3.00	3.00	2.00	4.00	4.00	3.00	1.50	5.00	4.30	3.00	1.00
Laportea aestuans (L.) Chew	Ur	A	4.00	3.00	3.00	2.00	3.00	3.00	3.00	1.50	3.00	3.00	2.00	1.50
Sida acuta Burn. F.	Ma	P	8.67	7.00	5.00	2.00	9.00	8.00	4.00	0.00	9.00	6.00	3.00	0.00
Sida rhombifolia L.	Ma	P	6.00	5.00	5.00	1.50	7.00	6.00	4.00	1.00	7.00	7.00	3.00	0.00
Stachytarpheta cayennesis (L. C. Rich.) Vahl.	Ve	P	3.00	2.00	3.00	1.50	3.00	3.00	3.00	1.50	3.00	3.00	2.00	1.00
Tridax procumbens L.	As	A	10.00	8.00	6.00	1.50	9.00	8.00	6.00	0.00	11.00	7.00	4.00	0.00
Grasses														
Cynodon dactylon (L.) Pers.	Po	P	3.00	6.00	2.00	3.00	8.00	5.00	2.00	2.00	6.00	4.00	2.00	1.00
Digitaris horizontalis Willd.	Po	A	6.00	5.00	5.00	2.00	6.00	4.00	3.00	2.00	5.00	4.00	2.00	1.00
Eragrostis tenella (L.) P. Beauv.	Po	A	4.50	3.50	3.00	2.50	4.50	3.50	3.00	2.50	3.00	4.50	3.00	1.50
Megathyrsus maximus (Jacq.) B. K. Simon & S. W. L. Jacobs	Po	P	8.00	7.00	4.00	4.00	7.00	6.00	4.00	4.00	6.00	6.00	4.00	2.00
Setaria barbata (Lam.) Kunth.	Po	A	6.00	4.00	3.00	3.00	6.00	6.00	2.00	2.00	5.00	5.00	3.00	1.00
Setaria longiseta P. Beauv.	Po	A	5.00	4.00	3.00	3.00	4.00	4.00	2.00	3.00	4.00	3.00	2/00	1.00
Sedges														
Cyperus esculentus Linn.	Cy	P	30.00	22.00	12.00	8.00	32.00	20.00	11.00	9.00	32.00	29.00	8.00	4.00
Cyperus rotundus L.	Cy	P	34.00	20.00	10.00	8.00	36.00	22.00	10.00	9.00	35.00	30.00	9.00	4.00
Mariscus alternifolius Vahl.	Cy	P	26.67	22.00	8.00	7.00	28.00	23.00	10.00	8.00	32.00	26.33	8.00	3.00

As = Asteraceae; Co = Compositae; Ny = Nyctaginaceae; Eu = Euphorbiaceae; La = Lamiaceae; Ur = Urticaceae; Ma = Malvaceae; Ve = Verbenaceae; Po = Poaceae; Cy = Cyperaceae; A = Annual; P = Perennial; PFC = Polyethylene Film Colour: B (blue), G (green) and W (transparent white); S = Soil Solarisation Duration: S_0 (No solarisation), S_2 (two weeks), S_4 (four weeks), S_6 (six weeks).

Table 4. Polyethylene Film Colour × Soil Solarisation Duration interactions effect on weed species diversity and flora abundance in hybrid maize field in 2017

Weed species	Family	Life cycle	PFC (B)				PFC (G)				PFC (W)			
			S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6
Broadleaves														
Ageratum conyzoides L.	As	P	12.00	8.00	4.00	2.00	13.00	6.00	3.00	2.00	11.00	6.00	3.00	0.00
Asipilia africana (Pers.) C. D. Adams.	Co	P	5.00	3.00	2.00	2.00	4.00	3.00	3.00	2.00	5.00	3.00	3.00	1.05
Boerhavia diffusa L.	Ny	P	6.00	5.00	3.00	2.00	8.00	4.00	2.00	2.00	6.00	4.00	2.00	1.50
Euphorbia heterophylla L.	Eu	A	8.00	5.00	3.00	2.00	8.00	5.00	2.00	2.00	7.00	4.00	3.00	1.50
Euphorbia hirta L.	Eu	A	7.00	5.00	4.00	2.00	8.00	5.00	2.00	3.00	7.00	6.00	3.00	1.00
Emilia sonchifolia (L.) DC.	As	A	5.00	4.00	2.00	1.00	6.00	3.00	2.00	2.00	5.00	3.00	3.00	0.00
Hpytis suaveolens (L.) Poit	La	A	4.00	2.00	3.00	3.00	3.67	3.00	3.00	3.00	3.00	2.00	2.00	1.00
Laportea aestuans (L.) Chew	Ur	A	3.00	2.00	3.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00	2.00	1.50
Sida acuta Burn. F.	Ma	P	6.00	5.00	3.00	2.00	6.00	4.00	2.00	3.00	7.00	3.00	2.00	1.00
Sida rhombifolia L.	Ma	P	6.00	4.00	3.00	2.00	6.00	3.67	2.00	2.00	5.00	4.00	3.00	1.00
Stachytarpheta cayennesis (L. C. Rich.) Vahl.	Ve	P	3.00	3.00	2.00	3.00	2.00	3.00	3.00	3.00	3.00	3.00	2.00	0.00
Tridax procumbens L.	As	A	7.33	7.00	3.00	2.00	8.00	5.00	3.00	2.00	9.00	4.00	3.00	0.00
Grasses														
Cynodon dactylon (L.) Pers.	Po	P	2.00	1.50	2.00	1.50	1.00	2.00	3.00	0.00	1.50	0.00	1.00	1.50
Digitaris horizontalis Willd.	Po	A	2.00	2.00	1.00	1.00	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.00
Eragrostis tenella (L.) P. Beauv.	Po	A	1.50	1.50	0.00	1.50	1.50	1.50	2.00	1.50	1.00	1.50	1.00	0.00
Megathyrsus maximus (Jacq.) B. K. Simon & S. W. L. Jacobs	Po	P	3.00	1.50	2.00	1.50	3.00	2.00	2.00	1.50	3.00	1.50	1.50	1.50
Setaria barbata (Lam.) Kunth.	Po	A	1.50	1.50	1.00	1.50	1.50	2.00	1.50	0.00	3.00	1.50	0.00	1.00
Setaria longiseta P. Beauv.	Po	A	1.50	1.50	0.00	1.50	1.50	1.50	2.00	0.00	2.00	1.50	1.50	1.50
Sedges														
Cyperus esculentus Linn.	Cy	P	4.00	2.00	4.00	3.00	4.00	4.00	3.00	2.00	5.00	3.00	2.00	1.50
Cyperus rotundus L.	Cy	P	5.00	2.50	2.50	2.50	4.00	3.00	2.00	3.00	4.00	3.00	2.00	1.50
Mariscus alternifolius Vahl.	Cy	P	4.00	3.00	3.00	2.00	5.00	4.00	4.00	3.00	5.00	3.00	2.00	2.00

As = Asteraceae; Co = Compositae; Ny = Nyctaginaceae; Eu = Euphorbiaceae; La = Lamiaceae; Ur = Urticaceae; Ma = Malvaceae; Ve = Verbenaceae; Po = Poaceae; Cy = Cyperaceae; A = Annual; P = Perennial; PFC = Polyethylene Film Colour: B (blue), G (green) and W (transparent white); S = Soil Solarisation Duration: S_0 (No solarisation), S_2 (two weeks), S_4 (four weeks), S_6 (six weeks).

Table 5. Polyethylene Film Colour × Soil Solarisation Duration interactions effect on weed species diversity and flora relative abundance in hybrid maize field in 2016

Weed species	Family	Life cycle	PFC (B)				PFC (G)				PFC (W)			
			S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6
Broadleaves														
Ageratum conyzoides L.	As	P	6.73	6.81	9.0	4.96	6.06	7.58	7.77	1.94	7.14	6.45	7.15	0.00
Asipilia africana (Pers.) C. D. Adams.	Co	P	2.89	2.48	2.73	2.48	2.33	2.33	3.88	1.94	3.13	2.15	3.57	1.69
Boerhavia diffusa L.	Ny	P	2.89	3.72	5.45	3.31	3.26	4.66	4.86	1.94	4.02	3.76	4.76	0.00
Euphorbia heterophylla L.	Eu	A	3.85	4.33	5.45	1.65	4.2	4.66	5.83	2.91	4.02	4.30	4.76	0.00
Euphorbia hirta L.	Eu	A	4.81	4.33	5.45	1.65	3.73	4.66	4.86	0.00	4.02	3.76	5.95	0.00
Emilia sonchifolia (L.) DC.	As	A	2.89	3.10	3.64	1.65	2.89	2.92	4.86	0.00	3.57	3.22	4.76	0.00
Hpytis suaveolens (L.) Poit	La	A	1.44	1.86	2.73	3.31	1.86	2.33	2.91	2.91	2.22	2.31	3.57	5.13
Laportea aestuans (L.) Chew	Ur	A	1.92	1.86	2.73	3.31	1.40	1.75	2.91	2.91	1.34	1.61	2.38	7.69
Sida acuta Burn. F.	Ma	P	4.17	4.33	4.55	3.31	4.20	4.66	3.88	0.00	4.02	3.22	3.57	0.00
Sida rhombifolia L.	Ma	P	2.89	3.10	4.55	2.48	3.26	3.50	3.88	1.94	3.12	3.76	3.57	0.00
Stachytarpheta cayennesis (L. C. Rich.) Vahl.	Ve	P	1.44	1.24	2.73	2.48	1.40	1.75	2.91	2.91	1.34	1.61	2.38	5.13
Tridax procumbens L.	As	A	4.81	4.95	5.45	2.48	4.20	4.66	5.83	0.00	4.91	3.76	4.76	0.00
Grasses														
Cynodon dactylon (L.) Pers.	Po	P	1.44	3.72	1.82	4.96	3.73	2.92	1.94	3.88	2.68	2.15	2.38	5.13
Digitaris horizontalis Willd.	Po	A	2.89	3.10	4.55	3.31	2.82	2.33	2.91	3.88	2.23	2.15	2.38	5.13
Eragrostis tenella (L.) P. Beauv.	Po	A	2.16	2.17	2.72	4.13	2.10	2.04	2.91	4.86	1.34	2.42	3.57	7.69
Megathyrsus maximus (Jacq.) B. K. Simon & S. W. L. Jacobs	Po	P	3.85	4.33	3.64	6.61	3.26	3.50	3.88	7.77	2.68	3.22	4.76	10.26
Setaria barbata (Lam.) Kunth.	Po	A	2.89	2.48	2.72	4.96	2.80	3.50	1.94	3.88	2.23	2.69	3.57	5.13
Setaria longiseta P. Beauv.	Po	A	2.41	2.48	2.72	4.96	1.86	2.33	1.94	5.83	1.79	1.61	2.38	5.13
Sedges														
Cyperus esculentus Linn.	Cy	P	14.43	13.62	10.91	13.22	14.92	11.66	10.68	17.48	14.28	15.58	9.53	6.00
Cyperus rotundus L.	Cy	P	16.32	12.38	9.09	13.22	16.78	12.83	9.71	17.48	15.62	16.12	10.72	20.50
Mariscus alternifolius Vahl.	Cy	P	12.83	13.62	7.22	11.59	13.05	13.14	9.71	15.53	14.28	14.15	9.53	15.39

As = Asteraceae; Co = Compositae; Ny = Nyctaginaceae; Eu = Euphorbiaceae; La = Lamiaceae; Ur = Urticaceae; Ma = Malvaceae; Ve = Verbenaceae; Po = Poaceae; Cy = Cyperaceae; A = Annual; P = Perennial; PFC = Polyethylene Film Colour: B (blue), G (green) and W (transparent white); S = Soil Solarisation Duration: S_0 (No solarisation), S_2 (two weeks), S_4 (four weeks), S_6 (six weeks).

Table 6. Polyethylene Film Colour × Soil Solarisation Duration interactions effect on weed species diversity and flora relative abundance in hybrid maize field in 2017

Weed species	Family	Life cycle	PFC (B)				PFC (G)				PFC (W)			
			S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6	S_0	S_2	S_4	S_6
Broadleaves														
Ageratum conyzoides L.	As	P	12.39	11.43	7.92	4.76	12.91	8.80	5.88	4.82	11.34	9.76	6.90	0.00
Asipilia africana (Pers.) C. D. Adams.	Co	P	5.16	4.29	3.96	4.76	3.97	4.40	5.88	4.82	5.15	4.88	6.90	0.00
Boerhavia diffusa L.	Ny	P	6.20	7.14	5.94	4.76	7.95	5.87	3.92	4.82	6.19	6.50	4.60	7.50
Euphorbia heterophylla L.	Eu	A	8.26	7.14	5.94	4.76	7.95	7.34	3.93	4.82	7.27	6.50	6.90	7.50
Euphorbia hirta L.	Eu	A	7.23	7.14	7.92	4.76	7.95	7.34	3.92	7.23	7.22	9.76	6.90	5.00
Emilia sonchifolia (L.) DC.	As	A	5.16	5.71	3.96	4.76	5.96	4.40	3.92	4.82	5.15	4.88	6.90	7.50
Hpytis suaveolens (L.) Poit	La	A	4.13	2.86	5.94	7.15	3.65	4.	5.88	7.23	3.09	3.25	4.60	5.00
Laportea aestuans (L.) Chew	Ur	A	3.10	2.86	5.94	7.15	2.98	2.93	5.88	7.23	3.09	4.88	4.80	7.50
Sida acuta Burn. F.	Ma	P	6.20	7.14	5.94	4.76	7.95	5.87	3.92	7.23	7.22	4.88	4.60	5.00
Sida rhombifolia L.	Ma	P	6.20	5.71	5.94	4.76	5.96	5.38	3.92	4.82	5.15	6.50	6.90	5.00
Stachytarpheta cayennesis (L. C. Rich.) Vahl.	Ve	P	3.10	4.29	3.96	7.15	1.99	4.40	5.88	7.23	3.09	4.88	4.60	0.00
Tridax procumbens L.	As	A	7.57	10.00	5.94	4.76	7.95	7.34	5.88	4.82	9.28	6.50	6.90	0.00
Grasses														
Cynodon dactylon (L.) Pers.	Po	P	2.07	2.14	3.96	3.57	0.99	2.93	5.88	0.00	1.56	0.00	2.30	7.50
Digitaris horizontalis Willd.	Po	A	2.07	2.86	1.98	2.38	1.49	2.20	2.95	3.61	1.56	2.44	3.44	0.00
Eragrostis tenella (L.) P. Beauv.	Po	A	1.55	2.14	1.98	2.38	1.49	2.20	2.95	3.61	1.03	2.44	3.44	0.00
Megathyrsus maximus (Jacq.) B. K. Simon & S. W. L. Jacobs	Po	P	3.00	2.14	3.96	3.57	2.98	2.93	3.92	3.61	3.09	2.44	3.44	7.50
Setaria barbata (Lam.) Kunth.	Po	A	1.55	2.14	1.98	3.57	1.49	2.93	2.95	0.00	3.09	2.44	0.00	5.00
Setaria longiseta P. Beauv.	Po	A	1.55	2.14	0.00	3.57	1.49	2.20	3.92	0.00	2.06	2.44	3.44	5.00
Sedges														
Cyperus esculentus Linn.	Cy	P	4.13	2.86	7.92	7.15	3.97	5.87	5.88	4.82	5.15	4.88	4.60	7.50
Cyperus rotundus L.	Cy	P	5.16	3.57	4.95	5.95	3.97	4.40	3.92	7.23	4.12	4.88	4.60	7.50
Mariscus alternifolius Vahl.	Cy	P	4.13	4.29	5.94	4.76	4.97	5.87	7.86	7.23	5.16	4.88	4.60	10.00

As = Asteraceae; Co = Compositae; Ny = Nyctaginaceae; Eu = Euphorbiaceae; La = Lamiaceae; Ur = Urticaceae; Ma = Malvaceae; Ve = Verbenaceae; Po = Poaceae; Cy = Cyperaceae; A = Annual; P = Perennial; PFC = Polyethylene Film Colour: B (blue), G (green) and W (transparent white); S = Soil Solarisation Duration: S_0 (No solarisation), S_2 (two weeks), S_4 (four weeks), S_6 (six weeks).

The superior performance of maize under a 6-week solarisation followed by a 4-week solarisation in this research could be attributed to their higher weed suppression relative to a 2-week solarisation and no solarisation (i.e., control). The longer duration of solar heating of the soil attained in the 6-week solarised plots could have had greater lethal effect on weed seeds and seedlings in the soil thereby reducing weed competition and enhancing crop growth. This finding aligns with that of Ibarra-Jiménez *et al.* (2012) who reported 27.4% to 63% increase in leaf area of dry beans due to soil solarisation for 30-60 days. In related research on rice, Neogi *et al.* (2017) obtained enhanced rice seedling growth due to soil solarisation. Similarly, Kapoor (2020) reported successive increase in plant height and leaf area of okra with 2-weekly incremental soil solarisation durations over a period of 4-8 weeks; all superior to the control (no solarisation). It has been reported that the common application period of solarisation is 1-2 months (4-8 weeks) (Frillman, 2019) for most annual crops, while 40 days solarisation enhanced the biomass and grain yields of legumes due mainly to effective weed control (Linke *et al.,* 1991).

On the other hand, the similarity in the vegetative performance of maize under a 2-week soil solarisation and no soil solarisation indicated that the two weeks period was apparently too short for soil solarisation to yield noticeable positive impact on the crop performance. Interactively, the best growth performance of hybrid maize obtained from solarisation with transparent white polyethylene for six weeks could be as a result of the best weed suppression obtained from this treatment combination.

Yield attributes and grain yield

The significantly shorter days to 50% flowering, greater number of seeds per cob and higher grain yield obtained from transparent white polyethylene film plot relative to black and green polyethylene film plots could be ascribed to better weed control and enhanced growth performance, especially leaf area of maize in the transparent film treatment. Amare and Desta (2021) noted that increase in crop growth, development and leaf area usually results in grater photosynthetic area and consequently greater crop yield. The present finding is similar to that of Al-Solimani *et al.* (2015) who reported that transparent sheets enhanced crop yield more than black and white sheets. Similarly, Abu-Gharbieh *et al.* (1991) reported higher yields of tomato, eggplant and cucumber under transparent polyethylene films than black polyethylene films.

The enhanced yield performance of maize in solarised treatments could be as a result of better weed control and better vegetative performance of the crop under solarisation compared with the control. This finding agrees with those of Saloum and Almahasneh (2015) and Ahmad *et al.* (1996), who reported significantly higher yield of maize under solarisation than non-solarisation. Linke *et al.* (1991) established that solarisation of weed-infested field resulted in higher percentage increase in crop yield than when a relatively weed-free field was solarized, indicating that elimination of weed interference was a major means by which solarisation enhances crop performance. Increased crop yield due to solarisation has been observed in several crops including okra (Kapoor, 2020), carrot (Frillman, 2019), lettuce (Al-Solaimani *et al.,* 2015; Candido *et al.,* 2011), eggplant (Alshammari, 2017), and dry beans (Ibarra-Jime ́nez *et al.,* 2012). The overall best yield performance of maize under a six-week solarisation with transparent white polyethylene film suggests that this treatment combination had the best potential among those studied for enhanced productivity of hybrid maize in the study area. This finding agrees with Saloum and Almahasneh (2015) who obtained higher grain yield of maize from plots solarized for 45 days. This also agrees with Marenco and Lustossa (2000) who observed that the longer the days of soil solarisation, the lower the weed incidence, and consequentially, improve the performance of the crop through reduced weeds competitiveness.

Weed density and biomass

Generally, the lowest weed density obtained under the transparent white polyethylene film compared with the black and green polyethylene film is in agreement with Setyowati *et al.* (2020), who reported differential reductions in weed density among various polyethylene film colours, with clear films as the most effective at low soil depth. The authors attributed the superior weed suppression by transparent film to its ability to allow more heat radiation pass through the transparent film and penetrate deeper into the soil profile.

The similarity in weed dry matter among the polyethylene films agrees with the findings of Candido *et al.* (2011); they report no significant differences in weed dry matter among plastic films in solarized crop field. On the contrary, Al-Solimani *et al.* (2015) reported significantly lower fresh weed weight under transparent polyethylene sheets compared with black and white polyethylene sheets. The significant reduction in weed density and weed dry matter as soil solarisation duration increased to six weeks aligns with the findings of Kapoor (2020) who reported weed suppression by solarisation in the order: 8 weeks > 6 weeks > 4 weeks >no solarisation. However, our finding disagrees with Seman-Varner and McSorley (2012) who obtained no differences in weed density among solarisation durations between two and six weeks. The greater weed suppression by the six-week soil solarisation duration in this research could be attributed to possible prolonged heating of the soil which could have led to the death of more weed seeds and propagules in this treatment compared with shorter solarisation durations, aligning with Sharma and Kumar (2013).

Overall, the best weed suppression was attained by the interaction effect of transparent white film and six-week soil solarisation period which indicated that this treatment combination was highly effective in weed control in the study. Thus, agreeing with Al-Solimani *et al.* (2015), who obtained significantly lower weed weight under transparent polyethylene sheet over black and white polyethylene sheets. Similarly, Das and Yaduraju (2008) obtained the lowest weed density when soil solarisation was done with transparent polyethylene for 45 days compared to soils with no solarisation. However, our finding differs from Hasing (2002), who reported better weed control under black than transparent films for either 34- or 53-day solarisation. Our results are in tandem with findings of several researchers on the superiority of soil solarisation over non solarisation in weed control (Ahmad *et al.*, 1996; Kapoor, 2020; Saloum and Almahasneh, 2015; Setyowati *et al.*, 2020).

Weed flora abundance

The predominance of broadleaf and perennial weeds in the study area could be attributed to the prior-cropping fallow period which supports the report of Akobundu (1987). The lower weed species abundance recorded under solarisation relative to the control indicated that solarisation was effective in reducing weed populations as observed in the lower weed density and weed dry matter from solarisation. This suggests that the heat transmitted through the polyethylene films was lethal to the seeds, seedlings and propagules of different weed species. Also, the physical barrier posed by the polyethylene films could have aided the smothering of emerging weed seedlings. On the contrary, weeds in the control plots where less heat must have been transmitted in the soil and no physical barrier present on the soil surface, had better opportunity to emerge and thrive. This finding is consistent with Kapoor (2020) who observed higher weed floras presence in non-solarised as against solarised plots. The high abundance of most weed floras under the two-week solarisation which was close to that of the control could be due to the shortness of this duration which may not have allowed enough heat accumulation and transmittance into the soil to kill more weeds. This finding agrees with Gul *et al.* (2013) who found that solarisation for a short duration (20 days) was not effective in weed control in onion field.

The elimination of many annual broadleaf and grass weed species from plots solarised for six weeks agrees with previous research findings that annual weeds were more susceptible to solarisation than perennials (Benlloglu *et al.*, 2005; Stapleton *et al.*, 2005; Candido *et al.*, 2011). Also, Seman-Varner (2005) reported optimum control of annual broadleaf and grass weeds under a six-week solarisation over two-week solarisation duration. Conversely, the prevalence of sedge weeds (*Cyperus* spp. and *M. alternifolius*) even in plots solarized for six weeks indicated their resistance to solarisation which agrees with previous findings (Candido *et al.*, 2011; Satour *et al.*, 1991).

Fromour findings, both the colour of solarisation material and the duration of solarisation significantly influenced weed dry matter as well as the growth and yield attributes of maize. Transparent plastic tarp was more effective in weed reduction compared to green and black which was translated into a better vegetative and yield performance of the maize crop. It is therefore recommended to solarise the soil for six weeks using transparent white polyethylene film for effective weed suppression and enhanced maize performance in the study area.

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