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Drip irrigation and mulching reduce weed interference and improve water productivity of spring maize

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Abstract

Drip irrigation and mulching were tested to minimize unproductive water loss through evaporation and weed interference. A field experiment was conducted during spring season of 2020 and 2021 in split plot design with three replications. The study includes six treatment combinations of drip irrigation methods (surface drip and subsurface drip irrigation) and mulching (black plastic, paddy straw and no mulch) along with one conventional furrow irrigation without mulching (as control) in main plots. Four weed control treatments (atrazine 1000 g a.i./ha as pre-emergence, two hand weedings at 30 and 60 days after sowing [DAS], weed free and weedy for whole crop growth period) were kept in the subplots. The combination of drip irrigation and mulches significantly enhanced leaf area index and crop biomass at 60 DAS than furrow irrigation. Integration of subsurface drip irrigation with plastic mulching resulted in the lowest weed density and biomass among main plots. Drip irrigation coupled with plastic and straw mulching resulted in 86 and 50% reduction in weed density and biomass, respectively, as compared to no mulching. Integration of subsurface drip with paddy straw mulch and black plastic mulch resulted in 17.1 and 15.5% higher maize grain yield, respectively, as compared to furrow irrigation. The highest irrigation water productivity (3.58 kg/m^3) was observed in combination of subsurface drip and paddy straw mulch followed by combination of subsurface drip and black plastic mulch (3.51 kg/m^3). Overall, straw mulching in drip irrigation system proved economical in terms of maize productivity.

Introduction

Maize (*Zea mays* L.), with great photosynthetic capability and higher grain yield potential, is cultivated in diverse agro-climatic zones. Being the most versatile crop, maize is cultivated in over 166 countries worldwide, adapting to a diverse range of soils, climate, biodiversity and management practices. It contributes to 37% of global food grain production. India recorded 30 million tonnes of production from an area of 9.9 M ha during 2020–21 (Vatta *et al.*, 2023). In northwestern India, maize cultivation during the spring season (end of January to mid-June) is gaining popularity, particularly among farmers in potato-growing regions. This is because it offers a more advantageous use of fields left vacant after the early harvesting of potatoes in the rice/maize–potato–spring maize cropping system. The surge in popularity is due to high average productivity (8 t/ha) of maize during the spring season compared to the main/monsoon season crop (6 t/ha). During the spring season, there is a lower incidence of insect-pests and diseases compared to monsoon season. However, the high evapotranspiration rates often exceeding 10 mm/day (Singh and Vashist, 2016) during the hot and dry months in the spring season contribute to reduced water-use efficiency. Furthermore, maize growth and development are sensitive to water stress, especially during flowering and pollination stages (Brar and Vashist, 2020). Numerous studies have shown that maize yield is a linear function of seasonal evapotranspiration (Kuscu *et al.*, 2013; Kresović *et al.*, 2016).

Punjab, also known as India's breadbasket, plays a crucial role in the nation's agriculture and food security. Nearly 99.9% of its land is irrigated (Brar *et al.*, 2022). The dominant rice–wheat cropping system in the state requires about 2000 mm irrigation water annually, with rice cultivation consuming around 1600 mm due to its semi-aquatic nature (Brar *et al.*, 2012). Unfortunately, this irrigation-intensive cropping system has contributed to the degradation of water resources in the state, leading to a rapid annual depletion of groundwater reserves by about 0.54 m (Arora and Kukal, 2017). Therefore, efficient utilization of available water resources has become a compelling necessity to augment crop growth, yield and water productivity.

Drip irrigation helps in precise application of water in the form of droplets in the immediate vicinity of roots, thereby covering larger area with given quantity of water without any adverse impact on crop yield. In recent years, mulch–drip irrigation systems have become widespread as a new comprehensive agricultural technique to save water, and complete mulching led to increased soil moisture storage of 0–200 cm soil depth (El-Metwally *et al.*, 2022a, 2022b). It consolidated the technical virtues of drip irrigation and mulching *viz.* integrated application of irrigation water and fertilizer, reducing soil-water evaporation, saving irrigation water and increasing yield and water-use efficiency (Qin *et al.*, 2016; Liu *et al.*, 2017; Tian *et al.*, 2017; Gao *et al.*, 2019). Plastic film mulch improved crop establishment and growth (Chalker-Scott, 2007), resulting in higher hundred-grain weight (Kunzová and Hejcman, 2009).

Spring maize (end of January to mid-June) is subjected to intense weed competition as it encounters both summer and winter season weeds during the growth period (Saudy, 2015). Since maize plants have an open canopy and are poor competitors to weeds in the early growth stages, weeds should be quickly combated to avoid yield reduction (Abou El-Enin *et al.*, 2023; Saudy and El-Metwally, 2023). In northwestern India, hand weeding is becoming a less common weed control method in maize due to rising labour costs and migration of labour to urban areas. Though herbicides are powerful weed control agents however, excessive reliance on herbicides may increase the problem of herbicide-resistant weeds (Culpepper *et al.*, 2004; Hull *et al.*, 2014), making current and future herbicide use more contentious. Currently, 333 distinctive cases of herbicide-resistant weeds (species × site of action) in maize have been identified worldwide (Heap, 2024). Therefore, it is imperative to implement alternate weed management methods which can keep weeds under check. The mulch–drip irrigation system ensures high productivity with less labour while controlling weed growth and pest-diseases to facilitate the management of cultivable land, meanwhile, encouraging farmland management (Díaz-Pérez *et al.*, 2012; Xu, 2019). Distinctive successes have been recorded via using soil mulching technique to control weeds and enhancing crop productivity (Saudy *et al.*, 2021; El-Metwally *et al.*, 2022a, 2022b). Limited studies have been conducted in northwestern India to investigate the integrative effects of drip irrigation and mulching on weed control and water productivity of spring maize. The primary objective of the experiment was to investigate the effect of drip irrigation and mulch integration on weed growth and water productivity of spring maize.

Materials and methods

Experimental site description and weather

The field experiment was conducted during the spring season of 2020 and 2021 at Research Farm, Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab, India. The experimental site is situated at an altitude of 247 m above mean sea level in the Trans-Gangetic agro-climatic zone at 30°54′N latitude, 75°48′E longitude. The weekly mean maximum air temperature exhibited a range of 17.6–41.3 and 20.7–38.0°C, while the weekly mean minimum temperature ranged from 4.9–27.9 to 6.3–26.5°C during 2020 and 2021, respectively (Supplementary Tables 1 and 2). Spring season is marked by low temperature during early (February; at sowing) and bright sunshine hours during mid and late (May–June; at flowering or maturity) of spring season. A total rainfall amounted to 152.8 and 117.8 mm during 2020 and 2021, respectively, was received during the crop season. Evaporation amounting to 94.2 and 104 mm was recorded during 2020 and 2021. Accordingly, number of drip irrigations were 11 and 14 during 2020 and 2021, respectively while ten times furrow irrigation was given during both years (Supplementary Table 3).

Soil physico-chemical properties of experimental site

The soil was loamy sand in texture. The soil was tested low in available nitrogen (175.4 kg/ha) and organic carbon (3.9 g/kg), whereas available phosphorous (25.7 kg/ha) and available potassium (345.6 kg/ha) were high in the 0–15 cm soil layer. The pH (7.6) and electrical conductivity (0.35 dS/m) were recorded to be in normal range. The average field capacity (determined by pressure plate apparatus as per Richards and Weaver, 1943) was 24.28 cm in the 0–100 cm profile with an average bulk density of 1.60 Mg/m^3. Saturated hydraulic conductivity was calculated by the constant head method (Klute and Dirksen, 1986). The stratified physical properties of the experimental site are given in Table 1.

Treatments and experimental layout

The experiment was laid out in a split plot design with three replications (Supplementary Fig. 1). Main plots consisted of six combinations of drip irrigation methods (surface drip and subsurface drip irrigation) and mulches (black plastic mulch of 25 μm thickness, paddy straw mulch 6 t/ha and no mulch) and one additional furrow irrigation (without mulch) treatment as the control (recommended practice). To prevent the interflow of water between plots, a buffer area of 1.0 m was maintained between the main plots. Four weed control treatments (atrazine 1000 g a.i./ha as pre-emergence, two hand weedings at 30 and 60 days after sowing [DAS], weed free for whole crop growth period and weedy for the whole period) were kept in subplots. The gross and net area of subplot was 5 m (length) × 3 m (width) and 4.6 m × 1.8 m, respectively.

Agronomic practices

The field was ploughed two–three times using mould-board plough followed by planking. Subsurface drips (dripper spaced at 30 cm) were laid in the respective treatments at 20 cm depth. The ridges were made using a tractor-mounted ridger in the east-west direction at a spacing of 60 cm. Sowing was done on 11th February and 12th February during 2020 and 2021, respectively, using a seed rate of 25 kg/ha. Five rows of crop were sown per plot with dibbling method on the southern side of eastwest ridges, keeping plant-to-plant spacing at 20 cm. The spray of atrazine (1000 g a.i./ha in 500 litres spray solution) was done using a hand-operated knapsack sprayer, on the same day in straw/plastic mulch/no mulch and furrow irrigation subplots after sowing as per treatment layout (Supplementary Figs 2 and 3). Thereafter, straw mulch at 6 t/ha was spread in the respective main plots and thickness of straw mulch was 2.5–3.0 inches. In plastic-mulched plots, surface drip (having a dripper spacing of 30 cm) was laid before mulching by plastic. Black plastic mulch (25μm thickness) was laid on ridges and was fixed in furrows by covering all edges of plastic mulch with soil mounds. Thereafter, holes for dibbling seeds were punched in the plastic mulch, and sowing was done. In weed-free subplots, weeds were not allowed to grow during whole crop season. Manual weeding was employed as the primary measure to ensure the absence of weeds in weed-free subplots. However, weeds were allowed to grow throughout the crop season in weedy treatment.

Table 1. Physical and chemical properties of soil profile at the experimental field

Depth (cm)	Bulk density (Mg/m^3)	Field capacity (cm)	Saturated hydraulic conductivity (mm/h)	Sand (%)	Silt (%)	Clay (%)
0–10	1.56	2.32	3.62	81.60	10.65	7.75
10–20	1.60	2.33	3.09	82.25	11.30	6.45
20–30	1.62	2.43	4.58	79.25	12.41	8.34
30–40	1.59	2.50	4.56	78.45	12.80	8.75
40–60	1.60	4.92	4.07	78.27	12.68	9.05
60–100	1.61	9.78	4.26	78.86	11.60	9.54

In the control plots (furrow irrigation plot), nitrogen at 125 kg/ha was applied in three equal splits. One-third of nitrogen and a full dose of phosphorous at 60 kg/ha were drilled at sowing. Considering high potassium content indicated by the soil test, no additional potassium was applied. The remaining nitrogen was applied in two equal splits at knee high and pre-tasselling stage through urea. In drip (surface and subsurface) irrigated plots, fertilizers were applied through the fertigation method. A Venturi system is integrated into the drip irrigation setup to facilitate the injection of fertilizers during the irrigation process. The recommended dose for fertigation in spring maize is 92 kg N and 48.8 kg P_2O_5/ha. Fertigation was started after 12 DAS of maize, followed by the application of 25% of the fertilizer in four equal splits during the first month on a weekly basis. Rest of the fertilizer was applied in equal splits on weekly basis up to the first week of May.

Irrigation methodology

The pre-sowing irrigation was applied to ensure good soil moisture conditions at the time of sowing. Later irrigations in drip-irrigated plots were applied for 22, 64, 120 and 130 min

Table 2. ANOVA results for weed density and biomass as affected by year, drip irrigation, mulches and weed control treatments

Source of variation	Year	Main plots (drip × mulch) + furrow irrigation	Drip	Mulch	Drip × mulch	Weed control	Drip × weed	Mulch × weed control	Drip × mulch × weed control
Grass weed density (numbers/m^2)									
df	1	6	1	2	2	3	3	6	6
F	1.169	989.566	38.775	570.468	0.304	6405.611	14.577	193.686	1.637
Significance (*P*)	0.282	<0.001	<0.001	<0.001	0.739	<0.001	<0.001	<0.001	0.144
Broadleaf weed density (numbers/m^2)									
df	1	6	1	2	2	3	3	6	6
F	1.497	429.464	33.900	570.429	0.375	4346.056	11.332	197.101	0.299
Significance (*P*)	0.223	<0.001	<0.001	<0.001	0.688	<0.001	<0.001	<0.001	0.936
Sedges weed density (numbers/m^2)									
df	1	6	1	2	2	3	3	6	6
F	2.423	1970.785	5.113	153.285	0.320	28844.509	1.720	52.680	0.519
Significance (*P*)	0.122	<0.001	0.026	<0.001	0.727	<0.001	0.167	<0.001	0.793
Grass weed biomass (g/m^2)									
df	1	6	1	2	2	3	3	6	6
F	2.158	199.716	72.639	258.897	9.583	1793.253	28.046	89.353	3.400
Significance (*P*)	0.144	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.004
Broadleaf weed biomass (g/m^2)									
df	1	6	1	2	2	3	3	6	6
F	1.420	358.313	60.828	280.248	3.828	2727.894	25.027	98.655	1.466
Significance (*P*)	0.236	<0.001	<0.001	<0.001	0.025	<0.001	<0.001	<0.001	0.197
Sedges weed biomass (g/m^2)									
df	1	6	1	2	2	3	3	6	6
F	1.024	168.108	19.302	122.971	3.306	2382.870	6.578	42.380	1.396
Significance (p)	0.313	<0.001	<0.001	<0.001	0.040	<0.001	<0.001	<0.001	0.223

Table 3. Integrative effects of drip irrigation and mulches on weeds at 60 DAS in spring maize

Treatment	Surface drip	Subsurface drip
Grass weed density (numbers/m^2)		
Plastic mulch	2*b	1*a
Straw mulch	7*d	5*c
No mulch	17*f	14*e
Furrow irrigation: 22g		
Broadleaf weed density (numbers/m^2)		
Plastic mulch	4*a	3*a
Straw mulch	15*c	11*b
No mulch	29e	25*d
Furrow irrigation: 32e		
Sedges weed density (numbers/m^2)		
Plastic mulch	6*a	5*a
Straw mulch	17*b	15*b
No mulch	28*c	24*c
Furrow irrigation: 36d		
Grass weed biomass (g/m^2)		
Plastic mulch	4*a	3*a
Straw mulch	10*c	6*ab
No mulch	25e	14*d
Furrow irrigation: 29e		
Broadleaf weed biomass (g/m^2)		
Plastic mulch	3*b	1*a
Straw mulch	21*d	12*c
No mulch	32*e	19*d
Furrow irrigation: 40f		
Sedges weed biomass (g/m^2)		
Plastic mulch	8*a	6*a
Straw mulch	14*b	11*ab
No mulch	31*d	21*c
Furrow irrigation: 39e		

Weed data were subjected to square root transformation ($x + 1$) before analysis; however, back-transformed actual mean values are presented with interpretation based on the transformed data.

Treatment means with the same letter are not significantly different according to Fisher's protected least significance difference test ($P < 0.05$). Asterisk denotes significant differences between drip irrigation–mulch treatments from furrow irrigation according to Dunnett's multiple comparison test.

during February, March, April and May, respectively, up to maturity (Supplementary Table 3). The discharge rate in surface and subsurface drips was maintained at 2.2 litres/h. In furrow irrigation plots, subsequent irrigations were applied at 2 weeks interval up to 10th April and thereafter at 1 week interval up to maturity. A water meter was installed to accurately measure the quantity of irrigation water applied in all experimental units.

Volumetric soil moisture was determined with Delta-T Devices PR2 soil moisture profile probe (Delta-T Devices, UK) for each treatment near the ridge, from 0 to 10, 10 to 20, 20 to 30, 30 to 40, 40 to 60 and 60 to 100 cm soil profile before and after irrigation. Soil samples were collected from each main plot at 0–100 cm depth using an auger both at sowing and at harvest. Soil moisture content was determined by a gravimetric method (oven dry basis) at the time of sowing and harvesting. The consumptive use (actual crop evapotranspiration) under different treatments was calculated using soil water balance(Singh *et al.*, 2015):

$$\mathrm{ET_a} = I + P - R - D \pm \Delta S \tag{1}$$

where $\mathrm{ET_a}$ represents actual crop evapotranspiration (mm), I represents the irrigation water precipitation, R is the surface runoff, D is the deep drainage and ΔS is the change in soil water storage. Runoff was (considered as) zero as sufficient dikes were maintained. Deep drainage has also been considered zero when the soil profile moisture storage was less than field capacity. Any excess moisture than field capacity storage due to rain or irrigation has been calculated as deep drainage (Dar *et al.*, 2017).

Observations on crop and weeds

Leaf area index (LAI) was recorded using a SunScan Plant Canopy Analyzer (Delta-T Devices, Cambridge, UK) during 12.00–14.00 h on a sunny day at 60 DAS. Two plants from border rows were chosen from each plot, cut at the base and dried in the sun for 48 h. Subsequently, the sun-dried plants underwent further drying in an oven at 60°C until a constant weight was achieved. The average weight was recorded and expressed as the crop biomass in g/plant at 60 DAS. Weed density was recorded at 60 DAS by placing a quadrate (0.5 m × 0.5 m). The data for weed density were recorded by categorizing species into grasses, broadleaf and sedges separately. Weed biomass was recorded at 60 DAS by cutting weeds at the ground level and then dried in a hot hair oven at 60 ± 2°C until constant weight. The random seed samples were drawn to record 100-seed weight. To compute stover and grain yield, an individual bundle of stover after removing cobs, from net plot was weighed and grains were weighed after threshing.

Water productivity

The irrigation water productivity was calculated to evaluate the benefit of irrigation water applied through economic crop production by the following equation (Brar *et al.*, 2019):

$$\mathrm{WP_I} = \frac{Y}{\mathrm{IWA}} \tag{2}$$

where $\mathrm{WP_I}$ is the irrigation water productivity, Y= is the grain yield (kg/ha) and IWA= is the irrigation water applied (m^3/ha).

Economics

The monetary requirements for all treatments were calculated for the crop growing period. Different economic indicators were calculated for the crop based on existing price of the inputs and outputs. Gross returns were calculated by considering the main product and was calculated based on minimum support price (256.94 USD/Mg) offered by the Government of India for maize (Anonymous, 2021). Variable cost of cultivation including water costs and fixed cost of drip irrigation/mulching system was worked out (Supplementary Tables 4 and 5). Though there is free

Table 4. Interactive effects of irrigation and weed control treatments on total weed density and biomass at 60 DAS in spring maize

Drip irrigation × weed control treatments	Total weed density (numbers/m^2)			Total weed biomass (g/m^2)		
	Surface drip irrigation	Subsurface drip irrigation	Furrow irrigation	Surface drip irrigation	Subsurface drip irrigation	Furrow irrigation
Atrazine at 1000 g a.i./ha as pre-emergence	66b	54a	128e	75b	49a	163d
Weedy for whole period	100d	82c	233f	121c	75b	233e

Weed data were subjected to square root transformation ($x+1$) before analysis; however, back-transformed actual mean values are presented with interpretation based on the transformed data.

Treatment mean values not connected by the same letter are significantly different according to Fisher's protected least significance difference test ($P < 0.05$). Small letters (a, b) are used to signify differences among treatments.

electricity to farmers in Punjab, the cost of irrigation water per unit cubic metre (0.11 USD for <10 m^3/day) as per guidelines issued by Punjab Water Regulation and Development Authority was included in the variable cost of cultivation (Anonymous, 2020). Benefit:cost (B:C) ratio was calculated by dividing gross returns with variable cost.

Statistical analysis

The pooled analysis of 2 years experiment was performed as experimental error for 2 years was homogeneous according to Bartlett's test of homogeneity of variance. The analysis of variance (ANOVA) was performed using IBM SPSS Statistics 19 with years, drip irrigation × mulch treatments, weed control treatments and their interaction as fixed effect. The blocks and block × treatments were considered as random effect while performing ANOVA. The weed data were square root transformed before analysis to normalize the variance distribution. However, the back-transformed means are also provided in this paper for more clarity, transparency and comprehension. The integrative effects of weed control treatments × mulch treatments in drip-irrigated plots were estimated by excluding the control treatment (Supplementary Table 6). Response variables of crop (growth and yield), weed (density and biomass), water productivity and economics were subjected to Fisher's protected least significance difference test for comparing the means ($P < 0.05$). To compare means of response variable of crop and weeds in drip × mulch (2×3) main-plot experimental groups against a control group (furrow irrigation) mean, post-hoc Dunnett's multiple comparison test was computed:

$$D_{\text{Dunnett}} = t_{\text{Dunnett}}\sqrt{\frac{2\text{MS}}{n}} \tag{3}$$

where MS is the mean square value and n is the sample size.

Results

The major grass weed species consisting of *Digitaria sanguinalis*, *Dactyloctenium aegyptium* and *Eragrostis tenella* was recorded. The major broadleaf weeds were *Oenothera laciniata*, *Chenopodium album*, *Coronopus didymus*, *Rumex dentatus* and *Gnaphalium purpureum*. One perennial sedge, *Cyperus rotundus* was also observed in the experimental field. The integration of drip irrigation with and without mulches significantly reduced density and biomass of grasses, broadleaf weeds and sedges compared to furrow irrigation treatment (Table 2). Mulching along with drip irrigation system resulted in 85–92% reduction in density and biomass of grass and broadleaf weeds compared to furrow irrigation system. The drip–mulch interaction was observed to have 80–83% lower density and biomass of sedges compared to no mulching and furrow irrigation (Table 3). Regardless of weed control measures, subsurface and surface drip-irrigated plots have 65–68 and 48–58% lower total weed density and biomass than furrow-irrigated plots (Table 4). It indicated that drip irrigation managed to keep weeds under check without any chemical weed control. Interestingly, subsurface drip-irrigated plots have statistically similar weed biomass to atrazine-treated surface drip-irrigated plots. This indicated that surface drip-irrigated plots will need chemical weed control measure to keep weeds under check while the subsurface drip irrigation system will keep weeds under check without any extra weed control measures. A subsurface drip irrigation system has the lowest weed density and biomass compared to a surface drip irrigation system (Supplementary Table 7). Plastic mulching resulted in significantly less total weed density and biomass as compared to straw mulching and no mulch. Plastic mulch resulted in 85 and 80% reduction in total weed density and biomass, respectively compared to no mulch (Table 5). Straw mulching resulted in 50% lower weed density and biomass than no mulching. Atrazine application resulted in improved weed control efficacy in mulched plots. Interestingly, plastic-mulched plots have significantly less

Table 5. Interactive effects of mulches and weed control treatments on total weed density and biomass at 60 DAS in spring maize

Mulches × weed control treatments	Total weed density (numbers/m^2)			Total weed biomass (g/m^2)		
	Plastic mulch	Straw mulch	No mulch	Plastic mulch	Straw mulch	No mulch
Atrazine at 1000 g a.i./ha as pre-emergence	16a	56c	108e	17a	60c	110e
Weedy for whole period	23b	87d	164f	36b	87d	171f

Weed data were subjected to square root transformation ($x+1$) before analysis; however, back-transformed actual mean values are presented with interpretation based on the transformed data.

Treatment mean values not connected by the same letter are significantly different according to Fisher's protected least significance difference test ($P < 0.05$). Small letters (a, b) are used to signify differences among treatments.

Table 6. ANOVA results for crop variables as affected by year, drip irrigation, mulches and weed control treatments

Source of variation	Year	Main plots (drip × mulch) + furrow irrigation	Drip	Mulch	Drip × mulch	Weed control	Drip × weed	Mulch × weed control	Drip × mulch × weed control
LAI at 60 DAS									
df	1	6	1	2	2	3	3	6	6
F	2.148	75.530	23.557	128.194	0.903	106.184	1.037	5.191	1.022
Significance (*P*)	0.145	<0.001	<0.001	<0.001	0.408	<0.001	0.379	<0.001	0.415
Crop biomass (g/plant) at 60 DAS									
df	1	6	1	2	2	3	3	6	6
F	19.398	14.292	13.390	17.571	0.310	84.504	0.929	0.644	0.407
Significance (*P*)	<0.001	<0.001	<0.001	<0.001	0.734	<0.001	0.429	0.695	0.873
100-grain weight (g)									
df	1	6	1	2	2	3	3	6	6
F	5.205	128.219	7.381	40.214	0.043	279.509	0.495	0.195	0.251
Significance (*P*)	0.024	<0.001	0.008	<0.001	0.958	<0.001	0.686	0.978	0.958
Grain yield (Mg/ha)									
df	1	6	1	2	2	3	3	6	6
F	5.890	510.862	10.264	112.410	0.292	530.640	0.037	6.714	0.022
Significance (*P*)	0.017	<0.001	0.002	<0.001	0.748	<0.001	0.990	<0.001	1.000
Stover yield (Mg/ha)									
df	1	6	1	2	2	3	3	6	6
F	2.596	317.564	24.137	36.874	1.937	335.308	0.068	0.294	0.041
Significance (*P*)	0.109	<0.001	<0.001	<0.001	0.149	<0.001	0.977	0.939	1.000
Irrigation water productivity (kg/m^3)									
df	1	6	1	2	2	3	3	6	6
F	43.491	106.950	2.557	27.275	0.073	8.394	0.009	1.626	0.005
Significance (*P*)	<0.001	<0.001	0.113	<0.001	0.930	<0.001	0.999	0.147	1.000
B:C									
df	1	6	1	2	2	3	3	6	6
F	93.021	13.648	0.043	25.109	0.008	2.211	0.002	0.236	0.001
Significance (*P*)	<0.001	<0.001	0.836	<0.001	0.992	0.093	1.000	0.964	1.000

weed density and biomass as compared to straw mulching, indicating that plastic mulch was more efficient in controlling the weeds.

The combination of drip irrigation and mulching techniques demonstrated a significant effect on the growth and yield of spring maize (Table 6). The integration of drip irrigation and mulches significantly increased the LAI compared to control, furrow irrigation (Table 7). In addition, crop biomass was recorded to be significantly higher with the use of surface drip–plastic mulch, subsurface drip–plastic mulch and subsurface drip–straw mulch as compared to furrow irrigation. The subsurface drip and plastic mulching led to higher LAI and crop biomass at 60 DAS (Supplementary Table 7). Integration of drip irrigation and mulches also had a significant impact on stover and grain yield. There was no significant difference in 100-grain weight among main plot treatments. However, higher stover yield was recorded under surface drip–plastic mulch, subsurface drip–plastic mulch and subsurface drip–straw mulch compared to furrow irrigation. The grain yield increased significantly with integration of drip irrigation and mulches compared to furrow irrigation control (Table 7). Integration of subsurface drip along with paddy straw mulch as well as black plastic mulch resulted in 20.6 and 18.3% higher maize grain yield, respectively, as compared to the yield obtained from conventionally furrow-irrigated crop.

The consumptive use of water was influenced by surface and subsurface drip irrigation in combination with plastic and straw mulches (Fig. 1). The highest consumptive use of 700.1 mm was recorded in conventional furrow irrigation treatment without mulch. Among drip irrigation treatments, the maximum consumptive use of 529.3 mm was recorded under surface drip–no mulch, whereas the lowest consumptive use of 494.3 mm was recorded under subsurface drip–plastic mulch. Both mulching

Table 7. Integrative effects of drip irrigation and mulches on crop growth, yield variables, yield, irrigation water productivity and economics

Treatment	Surface drip	Subsurface drip
LAI at 60 DAS		
Plastic mulch	4.32*ab	4.54*a
Straw mulch	4.16*bcd	4.27*abc
No mulch	3.71e	3.86de
Furrow irrigation: 3.95cde		
Crop biomass (g/plant) at 60 DAS		
Plastic mulch	80.30*ab	85.73*a
Straw mulch	73.72ab	79.58*ab
No mulch	71.72b	75.16ab
Furrow irrigation: 71.85b		
100-grain weight (g)		
Plastic mulch	30.31ab	31.41ab
Straw mulch	32.01ab	33.42a
No mulch	27.21b	28.39ab
Furrow irrigation: 28.97ab		
Grain yield (Mg/ha)		
Plastic mulch	8.57*ab	8.78*a
Straw mulch	8.72*a	8.95*a
No mulch	7.30c	7.64bc
Furrow irrigation: 7.42c		
Stover yield (Mg/ha)		
Plastic mulch	11.63abc	13.20*ab
Straw mulch	12.57*abc	13.61*a
No mulch	10.63c	11.17bc
Furrow irrigation: 10.95c		
Irrigation water productivity (kg/m^3)		
Plastic mulch	3.43*a	3.51*a
Straw mulch	3.49*a	3.58*a
No mulch	2.92*c	3.06*bc
Furrow irrigation: 1.24d		
B:C		
Plastic mulch	0.86*c	0.88*c
Straw mulch	1.51*b	1.55*b
No mulch	1.38*b	1.45*b
Furrow irrigation: 0.77a		

Treatment mean values not connected by the same letter are significantly different according to Fisher's protected least significance difference test ($P < 0.05$). Small letters (a, b) are used to signify differences among treatments. Asterisk denotes significant difference between drip irrigation–mulch treatments from furrow irrigation according to Dunnett's multiple comparison test.

methods (plastic and straw) resulted in 16.1–18.4% higher water productivity than no mulch (Supplementary Table 7). Mulching coupled with drip irrigation resulted in 17 and 182% more irrigation water productivity than drip irrigation (without mulching) and furrow irrigation (Table 7). In terms of water budgeting, furrow irrigation treatment had the lowest B:C (0.77). Among drip irrigation × mulch systems, straw mulching coupled with subsurface drip irrigation resulted in the highest B:C of 1.55 which was statistically similar to drip irrigation. This indicates that integration of drip irrigation with mulches is more economical in spring maize. The integration of plastic mulching with drip irrigation methods resulted in lower B:C than furrow irrigation due to imposition of high infrastructure cost and lower yield.

Discussion

The use of drip irrigation combined with mulching enhanced the growth and yield of spring maize as reflected through higher LAI and crop biomass in the combination as compared to flood irrigation. The better efficiency of drip irrigation accredits the precise radial distribution of irrigation water where the roots are concentrated near emitters, consequently leading to efficient absorption of nutrients from the soil volume (Sinha *et al*., 2017). Additionally, mulching has also been shown to have improved soil moisture retention, water infiltration by restraining run-off, protecting against rainfall splash (Mubarak *et al*., 2021; Salem *et al*., 2021), capturing rainfall and abating surface evapotranspiration which resulted in increasing crop yield and water productivity (Zhang, 2014). A study by Wang *et al*. (2020) reported that maize grain yield was improved by approximately 9–10% under mulch-drip irrigation systems as compared to furrow irrigation.

Weed density and biomass was less in combination of drip irrigation and mulching plots compared to flood irrigation. Subsurface drip was more effective in controlling weeds compared to surface drip irrigation. Precise water application *via* subsurface drip along with retention of crop residue round the year consequently reduces weed seed germination and enhances weed seed predation (Jat *et al*., 2019). Similarly, Shrestha *et al*. (2007) observed a dwindling weed density under subsurface drip irrigation, owing to the fact that subsurface drip leaves the top layer of soil devoid of moisture (Coolong, 2013). Additionally, Hussain *et al*. (2022) also reported maximum weed suppression of about 43–47% under plastic mulch treatment in maize as compared to the weedy check. Drip irrigation system resulted in 48–54% reduction in weed density and biomass as compared to furrow irrigation. Further, the coupling of drip irrigation with mulches effectively controlled weeds as compared to furrow irrigation. Among mulches, plastic mulch was more effective in controlling weeds compared to straw mulch. Retention of crop residue on the soil surface or covering soil surface with plastic mulch resulted in less solar light interception and physical hindrance (Kaur *et al*., 2021). Subsurface drip irrigation showed 80–85% reduction in density and biomass of grass, broadleaf weeds and sedges. Application of plastic and straw mulch led to 80–85 and 48–50%, respectively, reduction in weeds as compared to no mulch treatment.

Consumptive use under subsurface drip irrigation was observed to be less than surface drip irrigation. This might be due to the reduced soil evaporation under subsurface drip irrigation as compared to surface and furrow irrigation systems. The low consumptive use of crop might be due to use of plastic mulch. Plastic mulch limits water loss by preventing rapid evaporation from the soil surface (Sharma and Bhardwaj, 2017). In this study, a similar amount of irrigation water was applied at constant discharge rate (2.2 litres/h) in both the drip irrigation methods to maintain adequate soil moisture in the proximity of root zone for better crop growth and water productivity. The

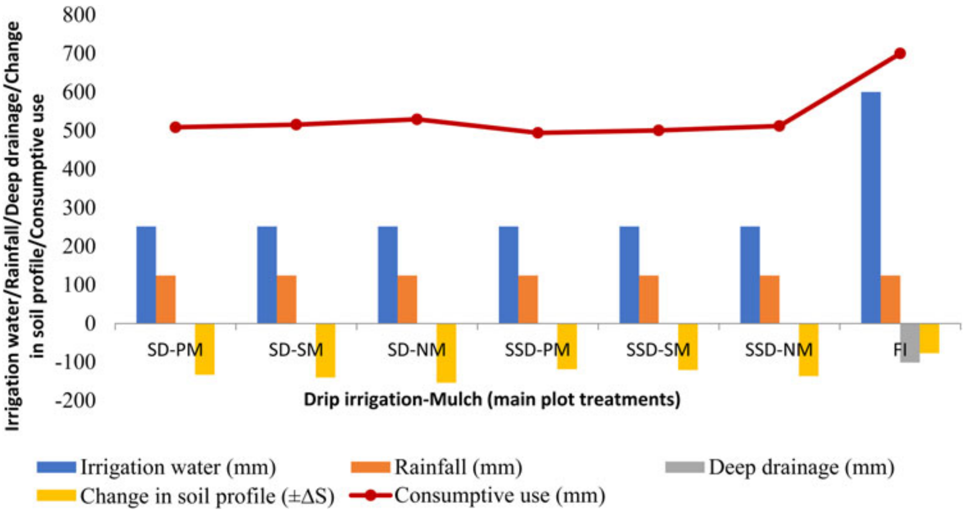

Figure 1. Effect of drip irrigation and mulching on soil water balance and consumptive use of spring maize. SD-PM, surface drip–plastic mulch; SD-SM, surface drip–straw mulch; SD-NM, surface drip–no mulch; SSD-PM, subsurface drip–plastic mulch; SSD-SM, subsurface drip–straw mulch; SSD-NM, subsurface drip–no mulch; FI, furrow irrigation.

wetting area around the emitter in the drip irrigation system is closely related to the rate of water application and irrigation frequency that plays vital role in evaluating volumetric moisture content, plant water uptake pattern and deep percolation (El-Hendawy *et al.*, 2008). Mulch–drip irrigation systems result in precise application of water near root zone and minimizes evaporation (Chakraborty *et al.*, 2008; El-Hendawy and Schmidhalter, 2010). This indicates that integration of drip irrigation and mulches are more economical in spring maize (Table 5). Mulch–drip irrigation systems result in improved fertilizer and water-use efficiency by diminishing the leaching and surface evaporation loss (Zhang, 2014; Fentabil *et al.*, 2016). It is worth to mention here that subsurface drip–plastic/straw mulch integration resulted in the least consumptive use despite the highest grain yield because of lower evaporation from the soil as water is being applied 20 cm below the surface under subsurface drip irrigation method. Secondly, in subsurface drip, profile water use was also the least among all treatments which resulted in the highest water productivity functions. These findings collectively suggested the positive integrative effects of subsurface drip with straw or plastic mulching on crop growth and water productivity from spring maize. Kang *et al.* (2017) reported a net gain of 1000 dollars/ha under a mulch–drip irrigation system as compared to conventional and sprinkler irrigation, and a saving of irrigation water up to 86% along with increased maize yield in northeast China. The highest consumptive use (700.1 mm) was recorded in conventional furrow irrigation treatment without mulch. The results demonstrated that integration of drip irrigation and mulching techniques resulted in improved irrigation water productivity as compared to the furrow irrigation treatment.

Conclusion

The high evaporative demand and interference of both summer and winter annual weeds increase the water requirement of spring maize in northwestern India. In this study, the combination effect of different drip irrigation systems and mulches (plastic and straw mulch) was evaluated in spring maize in comparison with the conventionally furrow-irrigated crop in the northwestern region of India. The results showed promising effect of drip irrigation along with mulches in enhancing LAI and crop biomass of spring maize. The highest grain yield was recorded under the integration of subsurface drip irrigation and straw mulch treatment relative to furrow-irrigated crop. Drip irrigation integration, with and without mulches, significantly decreased the density and biomass of grasses, broadleaf weeds and sedges compared to the furrow irrigation treatment. The subsurface drip–plastic mulch exhibited the lowest total weed density and biomass. Irrigation water productivity recorded under subsurface drip–straw mulch and subsurface drip–plastic mulch for spring maize crop were almost equal.

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