OPTIMIZING DEFICIT IRRIGATION AND SOIL MULCH ADAPTATION STRATEGIES FOR COTTON (*GOSSYPIUM HIRSUTUM* L.) PRODUCTIVITY AND ECONOMIC GAINS UNDER WATER-LIMITED DRY CLIMATIC CONDITIONS

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Abstract. Cotton is a major oil and fiber crop in many countries around the globe. The primary constraint in cotton cultivation is water scarcity. Thus, the adoption of economical and best management practices (BMP) are needed to improve productivity on a sustainable irrigation basis. We investigated the economic and agronomic benefits of sustainable irrigation [(control and partial rhizosphere drying (PRD)] and BMP (no-mulched, black plastic, wheat straw, and cotton stick) treatments, to find a combination of strategies towards a higher yield and economic return. Our findings revealed that PRD irrigation

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significantly increased cotton yield by 35%, improved water use efficiency (WUE) by 21%, and enhanced the economic returns of cotton production. Maximum expenditure was found in control irrigation treatment with wheat straw mulch. The control treatment, which involved full irrigation with cotton and wheat straw mulch, exhibited the highest recorded benefit-cost ratio (BCR) of 2.09:1. Conversely, the treatment that utilized PRD without the application of mulch material demonstrated the lowest BCR of 1.05:1. Maximum net field benefit (174514 Rs/ha) was recorded in a combination of control irrigation with wheat straw mulch. Among the PRD treatments, the maximum net field benefit was recorded in PRD with wheat straw mulch (89179 Rs/ha) followed by PRD with black plastic mulch (72236 Rs/ha), and minimum (84085 Rs/ha) net field benefit was recorded in PRD with cotton sticks mulch. The results showed that the combination of sustainable irrigation with BMP is a reliable strategy to increase WUE and economic gains to meet sustainable development goals in the era of global warming, climate change, and water crisis.
Keywords: *sustainable irrigation, BMP; benefit-cost ratio, dominance analysis, mulches, marginal rate of return, partial root-zone drying irrigation, water use efficiency*

Introduction

The world population is expected to reach about 9.2 billion by 2050. Therefore, global food production is necessary to increase by at least 70% to fulfill the demand. Crop production is adversely affected by various abiotic stresses, particularly water shortage or drought (Aslam et al., 2020; Iqbal et al., 2021; Raza et al., 2021). The water consumption for agricultural purposes is 67% and 19% for industry, and the rest is domestic utilization (FAO, 2017).

Cotton is a significant cash crop in many countries, mostly cultivated for its valuable fiber and oil. Pakistan ranked fourth in cotton production globally and was primarily established in areas with limited access to water (Tang et al., 2005; Iqbal et al., 2021). The cotton crop is more sensitive to environmental variation and very specific to its climatic conditions (Ahmad et al., 2016; Rahman et al., 2018). Both abundance and scarcity of water affect crop production however, water deficit is more critical and affects the growth and yield of cotton. It is anticipated that the amount of water available for crop production will decrease as a result of quick climatic changes like dry spells and rising demand from other competitive sectors (Zulfiqar et al., 2023).

Water shortage is reported to be the most critical stress for cotton production (Salem et al., 2021) critically controlling the development and yield (Rahman et al., 2019). Various management techniques have been developed to mitigate the negative effects caused by the drought but none was adopted by farmers on a larger scale due to high cost and specific requirements. Therefore, developing cost-effective management techniques not only minimize water use but also maintains crop productivity in an economical and practically feasible way. Mulching and halfway root zone drying/alternate wetting drying are two commonly studied management approaches that have been shown to save water, maintain yield, and improve profitability (Sajjad et al., 2018).

In the partial root-zone drying (PRD), periodically and alternatively half of the root zone is wetted and the other half is kept dry, permitting the dry zone of the root to become wet and the wet zone to get dry (Iqbal et al., 2019; Ahmad et al., 2020). The PRD has been used effectively in orchard crops such as pear, potato, peach, grapes, olive, oranges, and pomegranate (Abrisqueta et al., 2008; Hutton and Loveys, 2010; Ghrab et al., 2013; Parvizi et al., 2016). The dry portion of PRD-treated plants always produces more Abscisic acid (ABA) which improves the quality of agricultural products (Iqbal et al., 2019). Besides, alternative wetting-drying and mulch applications are economical and practically feasible approaches to increase productivity at farms.

Mulching is a water-saving management practice usually practiced in dry and semi-dry areas to reduce runoff and soil evaporation (Ahmad et al., 2015; Akhtar et al., 2018, 2019) conserving water (Iqbal et al., 2019; Ahmad et al., 2020) and controlling weed. Chopped Cotton sticks or rotavated cotton sticks in the field showed improved soil fertility and productivity/profitability of the next crop sown on the same land (Sajjad et al., 2018). The use of mulches is very helpful for profitable crop production especially in arid regions (Akhtar et al., 2019). Thus, the present study aimed to analyze the economics of various mulches with PRD and normal irrigation systems to access the most economic combination of mulch and PRD irrigation under semi-arid water-limited climatic conditions focusing on increased economic retunes in farmer's fields.

Materials and methods

Crop establishment and experimental set up

The study was carried out in Bahawalpur, Punjab province, Pakistan, which is characterized by hot and dry weather conditions. The diurnal temperature fluctuations are ranging from 26°C to 46°C in summer and 5°C to 24°C in winter. During the experimental period, the daytime average temperature was 4°C and the night-time average was 30°C. No rainfall occurred during the whole experimental period (*Fig. 1*). The soil texture is sandy loam with a pH of 8.4.

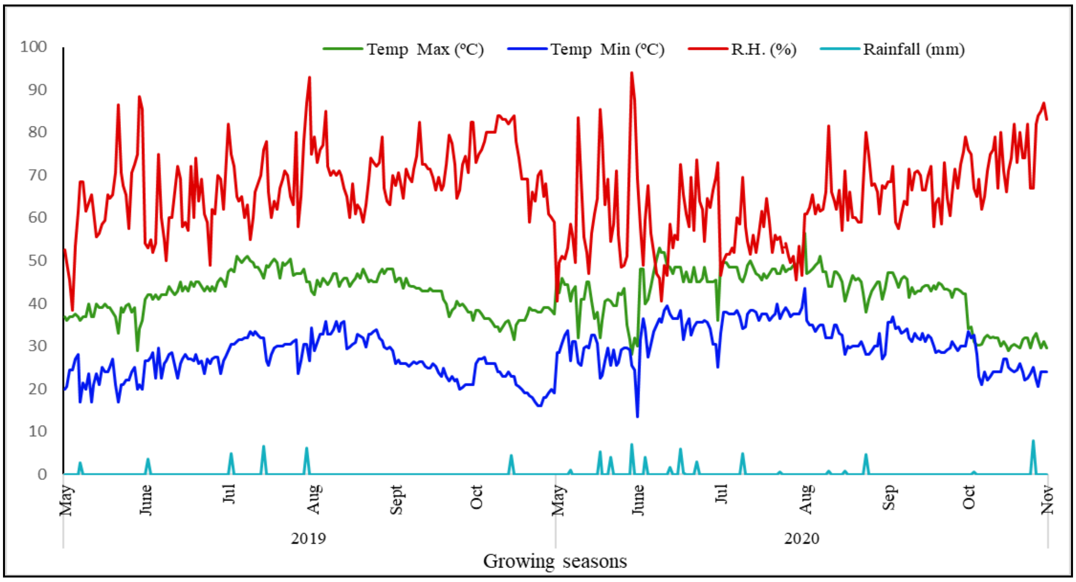

Figure 1. *Growing season (monthly) climatic data of the experimental site*

The treatment details for our experiments are as follows: The mulching treatment consisted of the following scenarios: M_0, representing no mulch/bare soil; M_1, involving black plastic mulch at a rate of 32 kg ha^{-1}; M_2, incorporating wheat straw mulch at a rate of 3 tons ha^{-1}; and M_3, using cotton sticks mulch at a rate of 10 tons ha^{-1}. These specific mulching options were chosen as best management practices (BMP) due to their easy accessibility and cost-effectiveness. Additionally, we employed two irrigation regimes: I_1, which represents partial root-zone drying (PRD) irrigation, and I_0, which is the control irrigation, serving as the second factor.

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For control treatment (I_0), 100% of evapotranspiration (ET) was replaced by irrigating in both the furrows, in PRD 50% of ET was replaced by applying water in alternate furrows. During the next irrigation phase, the remaining furrow (dry half portion of roots) was irrigated. The experimental field layout followed a randomized complete block design (RCBD) with a split-plot arrangement, having four replications. Keeping the irrigation regimes in main plots and mulches in sub-plots. The experiment was repeated in two seasons in 2019 and 2020.

The cotton seeds of the cultivar MM-58 were seeded in plots of 11 m x 22 m using furrow-bed systems after undergoing surface sterilization. A 5-meter gap was maintained between each plot to prevent water flow between the treatments. Each sowing bed is composed of three rows, with a spacing of 36 cm between the rows and 11 cm within each row. Each furrow had a width of 75 cm. All plants were irrigated equally until stand establishment and irrigation treatments were initiated 55 days after sowing, where 100% and 50% ET was replaced by irrigation in all and alternate furrow in control and PRD treatments, respectively. Mulch treatments were applied in the furrows and between the rows following the establishment of seedlings. The treatments continued until the final harvest. When more than 50% of the leaves began to wilt in the middle of the day, irrigation was implemented. The amount of water used on each experimental unit was documented. The application of fertilizer was carried out in accordance with the prescribed recommendations. The total water calculation at the end of the experiment in control treatment was 1050 mm with and without mulch application and a half (686 mm) was used in PRD with alternate irrigation using PMB (i.e., mulches) and un-mulched treatments.

Measurements

The plant height at maturity and leaf area index were measured using a meter scale and portable laser leaf area meter model CI- 2002L (CID BioScience, United States), respectively. The chlorophyll index was recorded using chlorophyll meter model CL-01 (Hansatech Instruments Ltd., United Kingdom) (Raza et al., 2017).

A fully expanded youngest leaf was selected to measure leaf fresh weight (FW). To compute the leaf turgid weight (TW), leaves were soaked for 18-20 h at 25°C and extra water was blotted using tissue paper. Leaf dry weight (DW) was measured after oven drying in three days at 70°C. The leaf relative water content was measured by the formula, LRWC (%) = FW – DW / TW – DW × 100. Excised leaf water loss (ELWL) from cotton leaf was taken as ELWL (%) = (FW – WW) / DW where WW represents the wilted weight. The leaf water potential was measured in fully stretched leaf at the top of the plant using water potential apparatus (Chas W. Cook Div., England). A vapor pressure osmometer (Wescor 5520, Logan, USA) was used to determine the osmotic potential of the leaf from the frozen sap of the crushed leaf. Turgor pressure (TP) of the leaf was measured using TP = osmotic potential (OP) – water potential (WP) (Raza et al., 2017). Porometer MK-3 (Delta-T Devices, Burwell Cambridge, England) Hertford, Herts, England) and infrared gas analyzer (Li-COR-LI 6250) were used to record leaf stomatal conductance and photosynthetic rate (Raza et al., 2017).

The soil moisture content (at 0-20 cm) was measured by oven-dry method (Ahmad et al., 2015). The WUE) of each growing season was calculated using following equation:

$$\text{Water use efficiency} = \text{Seed cotton (kg ha}^{-1}\text{)} / \text{Total water application (mm)}$$

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The net income, benefit-cost ratio, net field benefit, and marginal rate of return were calculated using standard approaches. Net income was calculated by deducting the cost of production from the income (CIMMYT, 1988 An Economics Training Manual). The benefit-cost ratio was worked out by dividing the net income ha^{-1} by the total cost involved ha^{-1}.

$$\text{Benefit–cost ratio} = \text{Net Income} / \text{Total Cost}$$

Net field benefits for each were calculated by subtracting the input cost of each treatment from the gross income of each treatment.

$$\text{Net benefits} = \text{Gross benefits} - \text{input cost}$$

where:

$$\text{Gross income} = \text{yield (kg ha}^{-1}\text{) per treatment} \times \text{unit cost of commodity}$$

The marginal rate of return (MRR) was calculated by adopting the following formula:

$$MRR = MNB / MC \times 100$$

where:
MRR = Marginal rate of returns, MNB = Change in net benefits, MC = Marginal cost.

$$MNB = \text{net benefit of treatment} - \text{net benefit of control}$$

Statistical analysis

Data were analyzed using STATISTIX software (version 9.2) and means were compared by least significant difference (LSD) at 5% probability level (Steel et al., 1997). Before analysis, data were tested for normality and homogeneity of variance.

Results

Growth and chlorophyll content

Irrigation regimes and various mulches as BMP scenarios had a significant effect on plant height and leaf area index of cotton (*Table 1*). Wheat straw (M_2) attained a significant (7.11 cm) plant height, and leaf area index compared with that of black plastic mulch. Further, a 55.8 cm taller plant, and leaf area index was produced by I_0 than I_1. The interaction effect of irrigation and straw mulch showed that 79.1 cm taller plants and leaf area index were produced by M_2I_0 compared with that of M_0I_1.

A considerable effect on leaf chlorophyll contents of cotton was observed under both treatments as shown in *Table 1*. Amongst the mulch treatments, M_2 showed the maximum leaf chlorophyll content (45.16%) followed by M_1 (43.25%) and the lowest value was observed in M3 (39.95%). For irrigation regimes (PRD vs. control) maximum chlorophyll content (46.45%) was recorded in I_0 and the lowest (36.01%) was recorded in I_1. Similar results were recorded in 2020. For both years, the interactions pertaining to the amount of chlorophyll were not statistically significant.

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Table 1. *Effect of different mulches and irrigation intervals on water-related parameters of cotton in field conditions*

	Plant height (cm)		Leaf area index		Excised leaf water loss (%)		Leaf chlorophyll contents (%)		Leaf relative water contents (%)		Leaf water potential (-MPa)	
	2019	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Mulches												
M_0	119.27 D	118.82 C	2.53 C	2.66 D	2.34 B	2.31 D	36.58 D	33.96 D	74.50 D	70.43 D	3.26 B	3.19 B
M_1	137.76 B	140.12 A	3.05 AB	3.14 B	2.81 A	2.59 B	43.25 B	40.30 B	81.00 B	76.25 B	3.08 C	3.04 C
M_2	144.87 A	140.08 A	3.30 A	3.29 A	2.83 A	2.68 A	45.16 A	43.55 A	84.50 A	79.70 A	3.40 A	3.33 A
M_3	130.52 C	130.02 B	2.81 BC	2.99 C	2.29 B	2.50 C	39.95 C	36.33 C	77.33 C	72.50 C	2.82 D	2.76 D
LSD	**1.1721**	**1.1879**	**0.2874**	**0.0459**	**0.3448**	**0.0161**	**1.19**	**1.22**	**0.76**	**1.77**	**0.03**	**0.0104**
Irrigation												
I_0 (control)	161.25 A	156.57 A	3.37 A	3.50 A	2.89 A	2.87 A	46.45 A	43.58 A	85.75 A	81.28 A	2.68 B	2.62 B
I_1 (PRD)	105.45 B	107.95 B	2.48 B	2.54 B	2.24 B	2.18 B	36.01 B	33.49 B	72.91 B	68.15 B	3.60 A	3.54 A
LSD	**0.7819**	**0.9930**	**0.2045**	**0.0421**	**0.2327**	**0.0110**	**0.96**	**0.67**	**0.50**	**0.73**	**0.01**	**0.0179**
Mul. × Irrig.												
M_0I_0	146.27 d	141.57 d	3.05	3.22 c	2.27	2.65	42.00	39.33	81.50 d	77.33777	2.72 g	2.64 g
M_0I_1	94.27 h	96.07 h	2.01	2.10 g	1.94	1.98	31.16	28.60	67.50 h	63.53	3.80 b	3.75 b
M_1I_0	166.11 b	161.00 b	3.60	3.55 b	3.24	2.94	48.50	45.06	87.50 b	82.13	2.77 f	2.72 f
M_1I_1	109.40 f	119.23 e	2.51	2.74 e	2.38	2.25	38.00	35.53	74.50 f	70.36	3.40 c	3.36 c
M_2I_0	173.33 a	168.97 a	3.74	3.75 a	3.17	3.03	50.33	46.56	90.50 a	86.16	2.83 e	2.76 e
M_2I_1	116.40 e	111.20 f	2.87	2.84 d	2.50	2.34	40.00	38.53	78.50 e	73.23	3.97 a	3.91 a
M_3I_0	159.30 c	154.73 c	3.10	3.49 b	2.43	2.86	45.00	41.36	83.50 c	79.50	2.42 h	2.37 h
M_3I_1	101.73 g	105.30 g	2.53	2.50 f	2.15	2.15	34.90	31.30	71.16 g	65.50	3.22 d	3.15 d
LSD	**1.5639**	**1.9859**	**N.S**	**0.0842**	**N.S**	**N.S**	**N.S**	**N.S**	**1.01**	**N.S**	**0.02**	**0.0358**
ANOVA												
Mulches (M)	0.00**	0.00**	0.0030*	0.00**	0.0134*	0.00**	0.00**	0.00**	0.00**	0.0001*	0.00**	0.00**
Irrigation (I)	0.00**	0.00**	0.00**	0.00**	0.0002**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Mul. × Irrig.	0.0014*	0.00**	0.2316NS	0.0016	0.2565NS	0.1010NS	0.933NS	0.5758NS	0.05*	0.1303NS	0.00**	0.00**

Significant differences are indicated by an asterisk (*); *$P \leq 0.05$, **$P \leq 0.01$; NS, non-significant. (M_0 = No Mulch/Bare soil, M_1 = Black plastic mulch, M_2 = Wheat straw mulch, M_3 = Cotton sticks mulch)

Water-related parameters

The treatments had a significant effect on excised leaf water loss. Wheat straw mulch showed the highest water loss in excised leaves (2.83%) than black plastic mulch (2.81%) and the lowest water loss was recorded in cotton sticks mulch (2.29%). Maximum excised leaf water loss (2.89%) was recorded in the control and minimum (2.24%) was recorded in the PRD irrigation technique. The interaction of both irrigation and mulches was non-significant for both years (*Table 1*). A similar trend was found in both years. Application of wheat straw mulch resulted in the highest value of leaf relative water contents (84.50%) compared to black plastic mulch = 81.00% and cotton sticks mulch = 77.33%. In the Irrigation treatments the maximum leaf relative water content recorded (85.75%) in the control, the minimum (72.91%) was recorded in PRD, showing same pattern during both seasons. Interaction across factors was significant in 2019, however, it was non-significant in 2020. Leaf water potential (LWP) was significantly affected by both treatments (irrigation and mulches) as shown in *Table 1*. In the mulch treatments, wheat straw (M_2) resulted in maximum negative LWP (-3.40 MPa) followed by un-mulched treatment (M_0 = -3.26 MPa). Minimum LWP was observed in cotton sticks mulch treatment (M_3 = -2.82 MPa). From irrigation treatments, maximum negative leaf water potential (-3.60 MPa) was measured in I_1(PRD), while the control had a value of (-2.68 MPa). Among the interaction terms, the highest value of LWP (-3.97 MPa) was recorded in M_2I_1 and the minimum LWP was observed in M_3I_0 (-2.42 MPa). Similar results were observed in the both seasons (2019, 2020).

Both treatments had a statistically significant effect on leaf osmotic potential (LOP) in cotton (*Table 2*). Mulch treatment M_2 achieved higher negative value of leaf osmotic potential (-19.00 MPa) than M_1 (-17.03 MPa) and M_3 (-15.50 MPa). From irrigation treatments, a higher negative value of LOP (-18.51 MPa) was recorded in PRD and a lower (-14.38 MPa) value of LOP was recorded in the control. The maximum negative LOP (-21.50 MPa) was recorded in M_2I_1 and the minimum value of LOP was measured in M_0I_0 (-12.50 MPa). A statistically significant effect on leaf turgor potential (LTP) was observed under-tested treatments (*Table 2*). The mulch-treatment M_2 recorded the highest LTP (16.61 MPa) than M1 (14.90 MPa) and the lowest LTP was observed in M_3 (13.48 MPa). Higher LTP value for irrigation (15.89 MPa) levels was seen in PRD and less LTP value (12.59 MPa) was attained in control. Amongst the interactions, the highest LTP (18.52 MPa) was recorded in M_2I_1, and the lowest LTP value was attained in M_0I_0 (10.78 MPa). In both seasons, the osmotic and turgor potential ensuing trend was the same.

Table 2. *Effect of different mulches and irrigation intervals on water-related parameters of cotton under field conditions*

	Leaf osmotic potential (-MPa)		**Leaf turgor potential (MPa)**		**Stomatal conductance (mmolm^{-2}s^{-1})**		**Photosynthetic rate (µmolm^{-2}s^{-1})**		**Soil moisture (%)**		**Number of sympodial branches per plant**	
	2019	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Mulches												
M_0	14.26 D	11.75 D	11.97 D	9.55 D	346.0 B	317.0 C	14.90 C	14.35 D	11.78 D	12.25 D	16.50 C	14.67 D
M_1	17.03 B	15.01 B	14.90 B	12.96 B	329.5 C	334.3 B	17.65 B	16.79 B	18.20 A	17.58 A	20.33 B	20.00 B
M_2	19.00 A	16.97 A	16.61 A	14.63 A	353.5 A	347.0 A	19.67 A	18.77 A	15.76 B	15.30 B	23.33 A	22.33 A
M_3	15.50 C	13.48 C	13.48 C	11.72 C	308.5 D	300.8 D	16.02 C	15.56 C	13.80 C	13.25 C	18.3 BC	17.50 C
LSD	**0.0458**	**1.0622**	**0.0115**	**1.0596**	**3.24**	**3.0564**	**1.32**	**0.66**	**0.48**	**0.62**	**2.3780**	**1.2788**
Irrigation												
I_0 (Control)	14.38 B	12.38 B	12.59 B	10.76 B	379.9 A	373.2 A	20.20 A	19.65 A	20.07 A	18.87 A	24.25 A	22.91 A
I_1 (PRD)	18.51 A	16.23 A	15.89 A	13.68 A	289.0 B	276.3 B	13.91 B	13.08 B	9.69 B	10.31 B	15.00 B	14.33 B
LSD	**0.0412**	**0.2635**	**0.0112**	**0.2605**	**1.41**	**1.72**	**0.51**	**0.90**	**0.34**	**0.42**	**1.7821**	**1.1369**
Mul. × Irrig.												
M_0I_0	12.50 h	10.50 e	10.78 h	8.86 f	389.0 b	383.0 b	17.00 d	16.50 d	16.50 d	15.50 d	21.00	19.00
M_0I_1	16.03 e	13.00 d	13.17 f	10.2 de	303.00 f	251.0 g	12.80 f	12.20 f	7.06 h	9.00 f	12.00	10.33
M_1I_0	15.03 f	13.03 d	13.23 e	11.31 d	378.0 c	371.7 c	21.00 b	20.43 b	24.50 a	23.50 a	24.67	24.00
M_1I_1	19.03 b	17.00 b	16.58 b	14.62 b	281.0 g	297.0 f	14.30 ef	21.16 ef	11.90e	11.67 e	16.00	16.00
M_2I_0	16.50 d	14.50 c	14.70 d	12.73 c	396.0 a	389.3 a	24.00 a	23.50 a	20.70 b	19.30 b	28.33	26.67
M_2I_1	21.50 a	19.44 a	18.52 a	16.53 a	311.0 e	304.7 e	15.33 e	24.05 e	10.83 f	11.30 e	18.33	18.00
M_3I_0	13.50 g	11.50 e	11.66 g	10.13 e	356.0 d	349.0 d	18.83 c	25.20 c	18.60 c	17.20 c	23.00	22.00
M_3I_1	17.50 c	15.47 c	15.30 c	13.32 c	261.0 b	252.7 g	13.21 f	12.92 ef	9.00 g	9.30 f	13.67	13.00
LSD	**0.0823**	**0.5270**	**0.0224**	**0.5210**	**2.82**	**3.45**	**1.02**	**1.8154**	**0.68**	**0.85**	**N.S**	**N.S**
ANOVA												
Mulches (M)	0.00**	0.0001*	0.00**	0.0001*	0.00**	0.00**	0.0005*	0.00**	0.00**	0.00**	0.002*	0.00**
Irrigation (I)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**
Mul. × Irrig.	0.00**	0.0005*	0.00**	0.0003*	0.0002*	0.00**	0.0006*	0.0075*	0.0002*	0.00**	0.9360^{NS}	0.9064^{NS}

Significant differences are indicated by an asterisk (*); *P ≤ 0.05, **P ≤ 0.01; NS, non-significant. (M_0 = No Mulch/Bare soil, M_1 = Black plastic mulch, M_2 = Wheat straw mulch, M_3 = Cotton sticks mulch)

Leaf gas exchange and soil moisture measurements

Results indicated that mulches and irrigation had a statistically significant effect on stomatal conductance. The M_2 attained the highest stomatal conductance (353.50 mmol m^{-2} s^{-1}) followed by M1 (329.50 mmol m^{-2} s^{-1}) and M_3 (308.50 mmol m^{-2} s^{-1}) respectively. Irrigation intervals resulted in maximum stomata

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conductance (379.75 mmol m^{-2} s^{-1}) in the control treatment and minimum (289.00 mmol m^{-2} s^{-1}) in PRD. The highest stomata conductance (396.00 mmol m^{-2} s^{-1}) was showed in M_2I_0 followed by M_3I_1 (261.00 mmol m^{-2} s^{-1}). The both factors (mulches and irrigations) had a significant effect on the photosynthetic rate (*Table 2*). The highest photosynthetic rate (19.67 µmol m^{-2} s^{-1}) was observed in wheat straw (M_2) followed by black plastic (M1 = 17.65 µmol m^{-2} s^{-1}) and the cotton sticks mulch (M_3 = 16.02 µmol m^{-2} s^{-1}). For irrigation intervals, the highest photosynthetic rate (20.20 µmol m^{-2} s^{-1}) was observed in the control treatment followed by (13.91 µmol m^{-2} s^{-1}) in PRD. Interactions of both factors were also statistically significant and the maximum photosynthetic rate (24.00 µmol m^{-2} s^{-1}) was observed in M_2I_0 and the lowest value was attained in M_0I_1 (12.80 µmol m^{-2} s^{-1}) following same pattern in both seasons.

The highest soil moisture retention was recorded in M_1 (18.20%) followed by (M_2 = 15.76%) and (M_3 = 13.80%). Results for irrigation intervals, show that the highest soil moisture (20.07%) was observed in control and the lowest (9.69%) was recorded in PRD. The interaction of both factors also showed significant results. Amongst the interactions, a higher value of soil moisture (24.50%) was measured in M_1I_0 and the lowest value was in M_0I_1 (7.06%). The tendency of results for the year 2020 was similar to 2019 for soil moisture percentage.

Yield traits and water use efficiency

Data revealed that both treatments had a significant effect on the number of sympodial branches per plant of cotton (*Table 2*). Wheat straw mulch (M_2) attained the highest number of sympodial branches per plant (23.33) followed by black plastic mulch (M_1 = 20.33) and cotton sticks mulch (M_3 = 18.33). Intended for irrigation intervals, more sympodial branches per plant (24.25) were counted in control (I_0) followed by (15.00) PRD (I_1) in same trend in the both seasons. Among the interactions, there was no statistically significant difference for both growing seasons.

As shown in *Table 3,* both factors had a significant effect on the number of bolls per plant of cotton. The M_2 achieved the higher number of bolls per plant (42.33) followed by black plastic mulch (M_1 = 40.17) and the least in M_1 (36.17). For irrigation treatments, the highest number of bolls per plant (43.83) was recorded in control, and minimum (32.25) was attained in PRD. Amongst the interactions, there was no statistically significant difference for both seasons. The 100-bolls weight was significant at both treatments (*Table 3*) where M_2 attained the highest 100-bolls weight (333.33 g) followed by black plastic mulch (M_1 = 325.00 g) and cotton sticks (M_3 = 317.33 g). For irrigations,100-bolls weight (356.25 g) was counted in control (I_0) and (271.92 g) was in PRD (I_0). The interactions were statistically significant showing maximum 100-bolls weight (373.33 g) in M_2I_0 and minimum in M_0I_1 (232.33 g) in the same trend in both seasons. Seed cotton yield (kg ha^{-1}) significantly affected by both treatments (*Table 3*); wheat straw (M_2) attained the highest seed cotton yield (3707.7 kg ha^{-1}) followed by black plastic mulch (M_1 = 3452.2 kg ha^{-1}) and cotton sticks mulch (M_3 = 3181.2 kg ha^{-1}). For irrigation intervals, seed cotton yield (3946.2 kg ha^{-1}) was measured in I_0 (control) and (2543.5 kg ha^{-1}) was measured in I_1 (PRD). Amongst the interactions, there was a statistically significant difference in 2019. Maximum seed cotton yield (4456.7 kg ha^{-1}) was calculated in M_2I_0 and minimum was computed in M_0I_1 (1934.0 kg ha^{-1}). Interactions of treatments were found insignificant in 2020.

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Table 3. *Effect of different mulches and irrigation intervals on yield-related parameters of cotton under field conditions*

	Number of bolls per plant		100-bolls weight (g)		Seed cotton yield (kg ha^{-1})		Biological yield (kg ha^{-1})		Harvest index (%)		Water use efficiency (kg ha^{-1} mm^{-1})	
	2019	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**	**2019**	**2020**
Mulches												
M_0	33.50 D	31.50 D	280.67 D	276.00 D	2638.2 D	2562.8 D	6521.7 C	6431.8 C	41.99	41.53	3.42 D	3.34 B
M_1	40.17 B	38.00 B	325.00 B	320.00 B	3452.2 B	3331.8 B	8104.8 B	8360.0 B	44.82	40.52	4.59 B	4.41 A
M_2	42.33 A	40.50 A	333.33 A	330.00 A	3707.7 A	3556.0 A	9234.8 A	8987.7 A	40.79	38.11	4.93 A	4.42 A
M_3	36.17 C	36.50 C	317.33 C	314.00 C	3181.2 C	3087.5 C	7997.2 B	7866.3 C	40.4	39.87	4.22 C	4.10 A
LSD	**0.3723**	**0.763**	**2.57**	**2.57**	**27.41**	**35.51**	**719.92**	**67.14**	**N.S**	**N.S**	**0.03**	**0.51**
Irrigation												
I_0 (control)	43.83 A	42.00 A	356.25 A	353.00 A	3946.2 A	3813.8 A	9531.5 A	9349.3 A	42.32	41.71 A	3.75 B	3.62 B
I_1 (PRD)	32.25 B	30.25 B	271.92 B	267.25 B	2543.5 B	2455.3 B	6397.8 B	6473.6 B	41.68	38.30 B	4.84 A	4.51 A
LSD	**1.0349**	**0.7443**	**1.27**	**3.8**	**16.43**	**45.21**	**499.2**	**30.57**	**N.S**	**2.32**	**0.02**	**0.34**
Mul. × Irrig.												
M_0I_0	39	37	329.00 d	326.00 d	3342.3 d	3229	8521	8427 d	40.22	39.32 abc	3.13 g	3.07
M_0I_1	28	26	232.33 h	256.00 g	1934.0 h	1896.7	4522	4437 h	43.77	43.74 a	3.68 f	3.61
M_1I_0	46	44	366.00 b	361.00 b	4143.0 b	4047	9931	9749 b	42.72	42.51 ab	3.94 e	3.85
M_1I_1	34.33	32	284.00 f	280.00 e	2761. 3 f	2616.7	6279	6971 f	46.92	38.53 bcd	5.25 b	4.97
M_2I_0	48.33	46	373.33 a	369.00 a	4456.7 a	4248.3	10529	10237 a	43.33	42.50 ab	4.24 d	4.04
M_2I_1	36.33	35	293.33 e	291.00 d	2958.7 e	2863.7	7941	7738 e	38.26	33.72 d	5.63 a	4.81
M_3I_0	42	41	356.67 c	356.00 b	3842.7 c	3731	9145	8985 c	43.01	42.52 ab	3.65 f	3.54
M_3I_1	30.33	28	278.00 g	272.00 f	2520.0 g	2444	6849	6748 g	37.79	37.22 cd	4.79 c	4.65
LSD	**N.S**	**N.S**	**2.54**	**7.61**	**32.86**	**N.S**	**N.S**	**61.15**	**N.S**	**4.64**	**0.04**	**N.S**
ANOVA												
Mulches (M)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.0006*	0.00**	0.3622^{NS}	0.2514^{NS}	0.00**	0.0066*
Irrigation (I)	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.00**	0.7369^{NS}	0.0095*	0.00**	0.0004*
Mul. × Irrig.	0.8810^{NS}	0.1658^{NS}	0.00**	0.0065*	0.0002*	0.1313^{NS}	0.0660^{NS}	0.00**	0.1875^{NS}	0.0095*	0.00**	0.4953^{NS}

Both treatment factors (mulches and irrigations) had a significant effect on biological yield (kg ha^{-1}) (*Table 3*) indicating the maximum biological yield (9234.8 kg ha^{-1} in wheat straw M_2 followed by black plastic mulch (M_1 = 8104.8 kg ha^{-1}) and cotton sticks mulch (M_3 = 7997.2 kg ha^{-1}). For irrigation intervals maximum biological yield (9531.5 kg ha^{-1}) was recorded in I_0 (control) and minimum (6397.8 kg ha^{-1}) was recorded in I_1 (PRD). Interactions for biological yield had no significant effect for both factors in the year 2019 but were found statistically significant in 2020. The both treatments showed no significant effect on the harvest index (%) (*Table 3*). For irrigation intervals harvest index was statistically non-significant in both irrigation levels (Control and PRD) for the first season (2019) but statistically significant for the second season (2020). Interactions of both treatments were non-significant for 2019 and statistically significant for 2020. Both the factors (mulches and irrigations) had a significant effect on the water use efficiency of the cotton crop (*Table 3*). Amongst the mulch treatments, M_2 showed the highest water use efficiency (4.93 kg ha^{-1} mm^{-1}) followed by black plastic mulch (M_1 = 4.59 kg ha^{-1} mm^{-1}) and cotton sticks mulch (M_3 = 4.22 kg ha^{-1} mm^{-1}). For irrigation intervals, water use efficiency (4.84 kg ha^{-1} mm^{-1}) was recorded in PRD (I_1) and (3.75 kg ha^{-1} mm^{-1}) was recorded in control (I_0). Among the interaction, there was a statistically significant difference in 2019. Maximum water use efficiency (5.63 kg ha^{-1} mm^{-1}) was counted in M_2I_1 and the minimum was recorded in M_0I_0 (3.68 kg ha^{-1} mm^{-1}). Interactions for 2020 season were not significant.

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Economic gains

Seed cotton yield

Results showed (*Table 4*) a significant effect of different combinations of mulches and irrigation regimes on seed cotton yield of cotton during both the year of study (2019 and 2020). The highest seed cotton yield was recorded in M_2I_0 (control irrigation with wheat straw mulch @ 3 tons ha^{-1}) during both years. (The yield was high in 2019 than in 2020 due to better environmental conditions). M_1I_0 (control irrigation with black plastic mulch @ 32 kg ha^{-1}) gave the second-highest value and minimum yield was found in (M_0I_1). The same trend was repeated for the second year of the study (*Table 4*).

Table 4. *Economic analysis of cotton during 2019 and 2020*

Treatment combinations	2019		2020	
	Seed cotton yield (kg ha^{-1})	Gross income ha^{-1} (Rs)	Seed cotton yield (kg ha^{-1})	Gross income ha^{-1} (Rs)
M_0I_0 (Control irrigation without any mulch)	3342.30 d	225585	3229.00 d	258320
M_0I_1 (PRD irrigation without any mulch)	1934.00 h	130545	1896.70 h	151736
M_1I_0 (Control irrigation with black plastic mulch @ 32 kg ha^{-1})	4143.00 b	279625	4047.00 b	323760
M_1I_1 (PRD irrigation with black plastic mulch @ 32 kg ha^{-1})	2761.30 f	186367	2616.70 f	209336
M_2I_0 (Control irrigation with wheat straw mulch @ 3 tons ha^{-1})	4456.70 a	300780	4248.30 a	339864
M_2I_1 (PRD irrigation with wheat straw mulch @ 3 tons ha^{-1})	2958.70 e	199665	2863.70 e	193299
M_3I_0 (Control irrigation with cotton stick mulch @ 10 tons ha^{-1})	3842.70 c	259335	3731.00 c	298480
M_3I_1 (PRD irrigation with cotton stick @ 10 tons ha^{-1})	2520.00 g	170100	2444.00 f	195520

The mean in the same column having different letters differ significantly ($\alpha = 0.05$)

Net field benefits (NFB)

The (M_2I_0) gave the maximum net field benefit of Rs. 139530 and 174514 during 2019 and 2020, respectively. The second higher net field benefit (129125 and 169160, respectively) was recorded in M_1I_0 while minimum net field benefits were recorded in the M_0I_1 combination of PRD irrigation without any mulch during both the year of study (*Table 5*).

Benefit-cost ratio (BCR)

The benefit-cost ratio (BCR) was calculated dividing gross income ha^{-1} by the total cost involved ha-1. A ratio greater than one is considered as viable of a system. M_2I_0 attained maximum BCR (1.86:1) for all the combinations followed by M_1I_0 (1.85:1) during the first year of study. However, M_1I_0 showed higher BCR than in M_2I_0 during the second year (*Table 5*).

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Table 5. *Fixed cost (a) (2019) for I_0 = 141500; 2020 for I_0 = 145600*

Sr. No.	Treatment combinations	2019 Cost that varied (b) (RS.) ha^{-1}	2019 Total expenditure (a + b) ha^{-1}	2019 Net field benefit (gross income – total expenditure) (RS.) ha^{-1}	2019 Benefit-cost ratio (gross income/total cost)	2020 Cost that varied (b) (RS.) ha^{-1}	2020 Total expenditure (a + b) ha^{-1}	2020 Net field benefit (gross income- total expenditure) (RS.) ha^{-1}	2020 Benefit-cost ratio (gross income/total cost)
1	M_0I_0 (Control irrigation without any mulch)	0	141500	84085	**1.59 : 1**	0	145600	112720	**1.77 : 1**
2	M_0I_1 (PRD irrigation without any mulch)	-17500 (exclude half irrigation charges)	124000	6545	**1.05 : 1**	-17500 (exclude half irrigation charges)	128100	23636	**1.18 : 1**
3	M_1I_0 (Control irrigation with black plastic mulch @ 32 kg ha^{-1})	9000	150500	129125	**1.85 : 1**	9000	154600	169160	**2.09 : 1**
4	M_1I_1 (PRD irrigation with black plastic mulch @ 32 kg ha^{-1})	9000-17500 (-8500)	133300	53067	**1.39 : 1**	9000-17500 (-8500)	137100	72236	**1.52 : 1**
5	M_2I_0 (Control irrigation with wheat straw mulch @ 3 tons ha^{-1})	19750	161250	139530	**1.86 : 1**	19750	165350	174514	**2.05 : 1**
6	M_2I_1 (PRD irrigation with wheat straw mulch @ 3 tons ha^{-1})	19750-17500 (2250)	143750	55915	**1.39 : 1**	19750 -17500 -2250	104120	89179	**1.85 : 1**
7	M_3I_0 (Control irrigation with cotton stick mulch @ 10 tons ha^{-1})	11000	152500	106835	**1.70 : 1**	11000	156600	141880	**1.90 : 1**
8	M_3I_1 (PRD irrigation with cotton stick mulch @ 10 tons ha^{-1})	11000-17500 (-6500)	135000	35100	**1.26 : 1**	11000 -17500 (-6500)	139100	56420	**1.40 : 1**

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Table 6. *Dominance analysis of treatments during 2019 and 2020*

Sr. No.	Treatment combinations	2019		2020	
		Cost that varied (b) (RS.) ha^{-1}	**Net income (gross income-total expenditure) (RS.) ha^{-1}**	**The cost that varies (b) (RS.) ha^{-1}**	**Net income (gross income-total expenditure) (RS.) ha^{-1}**
1	M_0I_1 (PRD irrigation without any mulch)	-17500 (exclude half irrigation charges)	6545	-17500 (exclude half irrigation charges)	23636
2	M_1I_1 (PRD irrigation with black plastic mulch @ 32kg ha^{-1})	9000-17500(-8500)	53067	9000-17500(8500)	72236
3	M_3I_1 (PRD irrigation with cotton stick mulch @ 10 tons ha^{-1})	11000-17500(-6500)	35100 D	11000-17500(-6500)	56420 D
4	M_0I_0 (Control irrigation without any mulch)	0	84085	0	112720
5	M_2I_1 (PRD irrigation with wheat straw mulch @ 3 tons ha^{-1})	19750-17500(2250)	55915 D	19750-17500(2250)	89179 D
6	M_1I_0 (Control irrigation with black plastic mulch @ 32kg ha^{-1})	9000	129125	9000	169160
7	M_3I_0 (Control irrigation with cotton stick mulch @ 10 tons ha^{-1})	11000	106835 D	11000	141880 D
8	M_2I_0 (Control irrigation with wheat straw mulch @ 3 tons ha^{-1})	19750	139530	19750	174514

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Dominance analysis

Dominance analysis is carried out as net field benefit (NFB). A treatment combination is denoted as dominant (D) when its variable cost is higher but the net field benefit was less than the net field benefit of preceding treatment combinations. Non-dominated treatments are more profitable than dominated treatments. In the present experiment treatment combinations M_2I_1, M_3I_1, and M_3I_0 showed dominated during both years (2019 and 2020) of study as they had more varying costs but gave less net field benefit (*Table 6*).

Marginal rate of return (MRR)

Marginal analysis expresses (additional/extra) benefit at the expense of marginal cost (cost other than fixed cost). Dominated treatment combinations were not considered for marginal analysis and only un-dominated treatments were selected for marginal analysis. Data revealed that in 2019 maximum rate of return (443%) in M_0I_1. Similar findings were recorded in 2020 with higher value (509%) of the return rate in M_0I_1 in 2019. Throughout both trial years, therapy M1I1 had the lowest marginal rate of return values.

Discussion

Partial root-zone drying (PRD) is an economically efficient technique as it involves the application of almost half the water used as compared to normal irrigation. Several studies revealed that PRD significantly enhanced water productivity in crop plants (Shahnazari et al., 2007; Sepaskhah and Ahmadi, 2010; Sajjad et al., 2018; Iqbal et al., 2021).

Partial rhizosphere drying and mulches as BMP have been shown a positive influence on the growth, development and yield of various crops in water-limited conditions (Sajjad et al., 2018). Plant height is key to attaining higher yields in cotton, as it helps the plant produce more leaves and photosynthates (Ahmad et al., 2015). Water shortage can limit plant growth and height and photosynthetic activity (Hussain et al., 2009; Basal et al., 2010). This study showed PRD-treated cotton plants had 34.82% (2019) and 31.25% (2020) compare to control treatment (100% ET). With the reduction of water application, the plant height of various cotton varieties decreased (Hussein et al., 2011; Yagmur et al., 2014). A comparison of BMP (i.e., mulched) and un-mulched treatments showed that taller plants treated with wheat straw 17.09% (2019) and 15.28% (2020) as compared to the un-mulched treatment. Mulches reflect the sunlight, reduce the evaporation losses and hence increase the moisture content of the soil in comparison to bare soil (Ahmad et al., 2015; Sajjad et al., 2018).

The water status of plants and water transpiration through the leaves are significantly influenced by the leaf area index. Drought stress reduces leaf expansion and also disturbs the photosynthesis process (Iqbal et al., 2019). PRD-treated plants showed 37.55% (2019) and 38.4% (2020) leaf area in comparison to normal irrigation. Leaf area adjustment is the main process responsible for it in cotton (Ahmad et al., 2015). Many studies showed less leaf area index in drought-stressed plants concerning normal irrigation (Randhawa et al., 2017; Ishfaq et al., 2018; Maqsood et al., 2022). Non-mulched treatment resulted in 33.40% (2019) and 27.51% (2020) less leaf area concerning wheat straw mulch which performed the best than other mulches. Halemani et al. (2010) and Ahmad et al. (2015) observed more leaf area of cotton mainly under controlled weeds and healthy cotton leaves under mulch application.

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The water potential of the leaf and excised leaf water loss are two ways to quantify leaf water stress. The water loss from excised leaf is greater in optimum irrigation 34.39% (2019) and 36.89% (2020) as compared to PRD treatment. Non-mulched treatment computed 26.77% (2019) and 22.02% (2020) excised leaf water loss as compared to wheat straw, which performed better than other mulches. Hussein et al. (2011) and Anjum et al. (2017) also found similar results.

The chlorophyll content is an excellent indicator of the photosynthetic rate (Yang et al., 2007). We found that PRD plants got 22.97% (2019) and 23.69% (2020) less chlorophyll than the normally applied irrigation. Khakwani et al. (2013) reported similar findings in cotton and wheat crops and noted a higher chlorophyll formation in fully irrigated plants in comparison to water-stressed plants. Among all the mulches, wheat straw mulch had the highest chlorophyll content. Non-mulched treatment showed less chlorophyll 19.42% (2019) and 22.53% (2020) as compared to wheat straw. Mulching positively affected cotton growth with high content of chlorophyll in leaves (Halemani et al., 2010; Ahmad et al., 2015).

Crop response can be evaluated with the help of stomata conductance grown in water-limited areas (Khakwani et al., 2012). PRD treatment plants showed 23.96% (2019) and 26.03% (2020) low stomata resistance than the optimal treatment. ABA production in PRD-treated plants is the main agent for regulation of stomatal conductance for water-saving of plants (Nilson and Assmann, 2007; Marsal et al., 2008). The enhanced ABA in PRD plants is improving the water use efficiency through stomatal regulation (Ismail et al., 2002). Though, stomata conductance values differ between PRD and normal irrigated plants, there is no significant effect on the photosynthetic rate or yield of the crop (Sepaskhah and Ahmadi, 2010). All the BMP combinations performed superior to the non-mulched treatment showing 2.12% (2019) less stomata conductance but during the second year (2020), cotton sticks mulch showed 13.34% less stomatal conductance than wheat straw mulch.

Photosynthesis is the process by which a plant grows and produces its overall output. PRD-treated plants showed 32.76% (2019) and 35.22% (2020) lower photosynthetic rate compared to control-treated plants. The rate of photosynthesis and stomata resistance are mostly affected by severe water stress (Zeiger and Taiz, 2006). The photosynthesis efficacy becomes very low when mesophyll cells drop their water potential beyond the optimum potential level (Zeiger and Taiz, 2006). Production of ABA in PRD-treated plants controls the resistance of plants' stomata (Nilson and Assmann, 2007; Marsal et al., 2008) resulting reduction of photosynthesis (Alkhaldi et al., 2012; Aslam et al., 2020). All the BMP had positive effects on both the irrigation levels than the un-mulched treatment which recorded 25.54% (2019) and 24.87% (2020) less photosynthesis. The primary causes of the increased photosynthetic rate in cotton were mulching and PRD, two methods of water saving.

Water amount in plant leaves is the main indicator to select the various varieties or cultivars for water-stressed conditions (Sánchez-Blanco et al., 2002). PRD-applied treatment showed 15.15% (2019) and 16.35% (2020) less relative water in leaves than in control treatment. PRD-treated plants have less cell division, so their leaves are smaller than the normal irrigated plants (Stikić et al., 2003). Cotton leaves had low water content under drought conditions (Parida et al., 2007; Baraiya et al., 2022). Mulches performed the best at both irrigation levels than the un-mulched treatment which attained 11.97% (2019) and 11.77% (2020) less leaf-relative water than the fully irrigated treatment due to less evaporation.

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Leaf water potential (LWP) showed 35.38% (2019) and 36.22% (2020) less water potential in the fully irrigated treatment comparison to PRD treatment. Non-mulched treatment showed 5.83% (2019) and 6% (2020) less value of water potential as compared to wheat straw.

Drought or salinity has a negative impact on the osmotic potential value (Saleh, 2012). Normal water-applied treatment achieved 23.58% (2019) and 25.27% (2020) fewer negative values as compared to PRD-treated plants. Using various mulch materials, more leaf osmotic potential value was recorded in the wheat straw which was 26.33% (2019) and 32.68% (2020) more than the non-mulched plants.

Leaf turgor potential is mostly dependent on the relative water content of the leaf. PRD irrigated treatment showed 22.16% (2019) and 23.02% (2020) higher leaf turgor potential as compared to control irrigation levels. The leaf water potential and relative water content have positive interaction with the turgor pressure in various crops (Raza et al., 2014, 2017). Among the various mulch treatments, higher leaf turgor potential was observed in the wheat straw which was 29.72% (2019) and 37.27% (2020) more than the non-mulched treatment.

The proportion of moisture in the soil changes depending on the kind of soil, local climate, and crop’s water delta. PRD irrigated treatments showed 54.43% (2019) and 47.90% (2020) less value of soil moisture content than the control irrigation treatments. This large fluctuation is due to the reason that in PRD we conserved 50% of water by alternating the furrow irrigation. For mulch treatments, a higher percentage of soil moisture was recorded in black plastic mulch which was 26.96% (2019) and 32.14% (2020) more than the non-mulched treatment. Mulch materials made favorable conditions for cotton plants by conserving the water status in soil by reducing of weeds population (Ahmad et al., 2015).

The production and retention of bolls in cotton crops are mostly impacted by heat or drought stress. Less number of bolls per plant in drought was generally owing to fewer branches and short height if plants. Normal irrigation applied treatment attained 27.03% (2019) and 28.65% (2020) higher number of bolls/plant compared to PRD treatment. Ullah (2009) reported that the number of bolls per plant decreased under drought stress. A higher number of bolls under mulch treatments were due to the higher water retention and controlled weeds under mulching provides favorable conditions for plant growth compared to non-mulch treatment. Among the different mulches used in the experiment, wheat straw attained 21.36% (2019) and 22.78% (2020) more bolls per plant in comparison to non-mulched treatment. Venugopalan et al. (2009) recorded a higher number of cotton bolls in mulched treatment in comparison to non-mulched.

The number of sympodial branches per plant is also an important yield determinant of cotton. Normal irrigation applied treatment attained 39.78% (2019) and 39.16% (2020) more branches as compared to PRD treatment. Ullah (2009) reported that the number of branches per plant decreased under drought stress. Treatments covered with wheat straw mulch produced 30.58% (2019) and 35.91% (2020) more sympodial branches as compared to no mulch treatment.

Boll weight plays a key role in increasing seed cotton yield. PRD-applied treatments got 23.73% (2019) and 24.36% (2020) less value for the boll weight of cotton as compared to normal irrigation. Basal (2010) reported a decrease in bolls weight with decreasing the amount of water applied. Treatments in which wheat straw mulch produced 15.84% (2019) and 16.41% (2020) more bolls weight than the control (no mulch) treatment. When compared to an unmulched treatment, the increased value of

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boll weight in the mulched treatment is mostly attributable to the increased retention and conservation of soil moisture, which aided in a greater photosynthetic rate and, eventually, a higher assimilates partitioning.

Water scarcity or drought disturbs all the growth, physiology, metabolic, yield attributes, and finally the fiber quality in cotton crops. Normally applied irrigation (control) treatment attained 35.54% (2019) and 35.62% (2020) more cottonseed as compared to partial rhizosphere drying (PRD) treatment. Ullah (2009) and Ahmad et al. (2020) concluded that seed cotton yield decreased in drought treatment. Amongst the different mulches, wheat straw got 28.84% (2019) and 27.93% (2020) more cottonseed as compared to un-mulched treatment. More seed cotton yield in mulch treatments was due to more moisture retention in soil, improved growth, more photosynthetic rate, and ultimately the higher yield attributes concerning non-mulched treatment (Sajjad et al., 2018).

In our study, PRD-applied treatment attained 32.87% (2019) and 30.75% (2020) less biological yield as compared to control treatment. Wheat straw produced 29.37% (2019) and 28.43% (2020) higher value of biological yield than un-mulched treatment. These observations are per the findings of Yuan and Wu Qun (2006) who reported higher biological yields of cotton under straw mulch and polythene mulch compared to non-mulched treatments.

Water use efficiency (WUE) is an imperative attribute to compute the drought tolerance of crop species. PRD-applied treatment attained 22.52% (2019) and 19.43% (2020) more WUE as compared to control treatment. Similar findings for PRD were also proposed by Liu et al. (2007) and Adu et al. (2018). The higher value of WUE in mulched treatment was due to fewer evaporation losses and more water conservation. Treatments covered with wheat straw mulch showed 30.62% (2019) and 24.43% (2020) higher WUE compared to the control (no mulch) treatment.

In the current investigation, mulch treatments resulted in higher seed cotton yields. Rao et al. (2016) grew tomatoes under mulches and reported more economic yield and net field income under black plastic mulch as compared to un-mulched treatment (Rs. 212400 vs Rs. 394500) due to less increase in investment cost but more increase in economic yield under black mulch treatment. Similarly, the benefit-cost ratio (BCR) and marginal rate of return (MRR) were also more in treatment covered with black plastic mulch.

More net field benefits and marginal returns were recorded under the mulch application. Rao et al. (2016) also reported that although the initial cost of black plastic mulch is higher than control (un-mulched) treatment it significantly increased the final yield and net field returns of watermelon as compared to un-mulched treatment. The benefit-cost ratio was also less in un-mulched treatment when compared with black plastic mulch treatment.

More gross income and net income from yam production were achieved under the application of mulches as compared to un-mulched treatment (Akinola and Owombo, 2012). An increase of 34.65% in the cost-benefit ratio was obtained under mulch treatment as compared to treatment without any mulch. Similarly, the marginal return was also higher in mulch treatment. Higher profitability using mulches is mainly due to less water requirement, sufficient weed control, and less labor requirement (Rao et al., 2016). The results of the study supported by (Ahmad et al., 2015) They noted greater water conservation and adequate weed control under various mulch types, which lessens the labor-intensive need for weedicide spraying or hoeing.

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Conclusions

Partial root-zone drying is an efficient water-saving technique, with the potential to improve the yield and water use efficiency of cotton under arid climatic conditions. The combination of control irrigation treatment with wheat straw mulch as a BMP yielded the most profit, according to bioeconomics research on cotton production. Among PRD combinations with all mulches, maximum profit was obtained with wheat straw mulch followed by PRD with black plastic mulch and minimum in PRD irrigation with cotton sticks mulch. We showed that PRD is a profitable technique used either alone or in combination with mulches under water-limited conditions. Future, research should be directed towards studying the impact of various treatments in combinations for the future as climate variability is the main threat to sustainable cotton production. The results suggested a combination of PRD with BMP, as sustainable irrigation, to improve WUE and economic gains which are essential to meet sustainable development goals in the era of global warming, climate change, and water crisis.

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