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Productivity, water use efficiency and soil properties of sugarcane as influenced by trash mulching and irrigation regimes under different planting systems in sandy loam soils

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Introduction: In the era of climate change, sugarcane used to face a problem associated with water shortage due to erratic rainfall patterns and lowered water tables. Improved water use efficiency using innovative crop management strategy is needed for sustainable sugarcane production. Trash mulching with different irrigation regimes can effectively modify the plant's hydrothermal micro-environment for increasing cane yield and water productivity.

Methods: Keeping this in the background, a field experiment was conducted at Sugarcane Research Institute, RPCAU, Pusa, India, from 2016–17 to 2018–19 to investigate the effects of trash mulching and irrigation regimes on sugarcane productivity, water use efficiency (WUE) and soil properties in different planting systems. The field experiment comprised 12 treatments including four planting methods viz. conventional flat planting (CF; 75 cm row spacing) with trash mulching (6 t ha^{-1}), CF planting (75 cm row spacing) without trash mulching (6 t ha^{-1}), paired row trench (PT) planting (30: 120 cm row spacing) with trash mulching (6 t ha^{-1}), PT planting (30: 120 cm row spacing) without trash mulching (6 t ha^{-1}) and three irrigation schedules consisted of irrigation water (IW); cumulative pan evaporation (CPE) ratio of 0.60, 0.80, and 1.00 was laid out in strip plot design with three replications.

Results and discussion: The cane yield (103.5 t ha^{-1}) was found significantly higher in PT planting with trash mulching over the CF planting method with or without mulching. Concerning irrigation regimes using the IW/CPE ratio, it was found that the IW/CPE of 0.6 resulted in 16.9, 13.3% higher water-use efficiency, and 37.1, 40.7% higher water productivity over those under IW/CPE of 0.8, and 1.00, respectively. Furthermore, soil parameters like soil microbial biomass carbon (SMBC) and dehydrogenase activity were increased by 12.5, and 17.5 % due to trash mulching with trench planting as compared to those under conventional flat planting without mulching. The results suggest that planting sugarcane in paired rows and irrigation scheduling at 1.00 IW/CPE with the adoption of trash mulching practices is effective for increasing profitability by way of higher sugarcane productivity and water productivity and also in sustaining soil health.

KEYWORDS

cane yield, irrigation scheduling, mulching, planting methods, water productivity, water use efficiency

1 Introduction

Sugarcane is not only used for sugar production, but it is also becoming a major biofuel crop due to its exceptional dry matter yield. Several factors affect the production of sugarcane, including climate, soil type, crop management techniques, nutrient management (Kumar et al., 2023a), irrigation scheduling, and soil moisture availability during the growth phase (Sulaiman et al., 2015). Despite being a C_4 crop, sugarcane has a very high water requirement due to its long formative phase, during which it remains young and tender, as well as the hot and desiccating summer when evaporative demand is high (Wiedenfeld, 2000).

Using trash mulch in these circumstances is especially beneficial since it protects the soil's surface from evaporation loss by acting as a barrier to direct contact with solar radiation and also inhibits weed growth through the smothering effect. Therefore, mulching exerts direct and indirect effects on microclimates and increases yields and water productivity (Jiang et al., 2016; Yang et al., 2023). Additionally, crop residue layers can cut down surface evaporation by up to 50% in comparison to bare soil (Denmead et al., 1997; Kingston et al., 2005). Braunbeck and Magalhaes (2010) and Aquino et al. (2017) demonstrated that maintaining soil cover reduces soil moisture losses by 70%, minimizes soil erosion, improves soil physicochemical properties, and improves soil microbes in sugarcane. Sufficient soil moisture must be available throughout the crop growth period to achieve high yields (Kumar et al., 2013). On the other hand, traditional irrigation management issues include inadequate capacity for peak demand, unpredictable supply rates, and poor irrigation efficiency and regularity (Rajput et al., 2022). With the pan evaporation irrigation scheduling approach, farmers can change the amount of water used from one irrigation system to another without changing the amount of water used in each irrigation system and rainfall is also taken into account. Based on this approach, irrigation schedules can be computed, provided pan evaporation does not vary much during the growing season (Singh et al., 2007).

Agricultural productivity in arid and semiarid areas of South Asia is limited by a lack of precipitation and low water availability (Zhang D. Q. et al., 2005; Turner and Meyer, 2011; Pramanick et al., 2023); due to the significant impacts of global climate change on agricultural systems, this issue has become even more important (Gan et al., 2009; Singh et al., 2021). A large part of the country is under intensive agriculture and mostly irrigated by groundwater which has significantly contributed toward increased food production in India (Dangar et al., 2021). Over the last 10 years in India, the depletion of the groundwater table has increased by ~23% for irrigation (Dalin et al., 2017). Furthermore, intensive pumping and unregulated use of water have caused rapid declines in water tables, putting crop production at risk (Ahmad et al., 2023). Earlier sugarcane productions were still conducted using the conventional planting system. However, in order to deal with this issue, new plantation techniques have been developed to guarantee greater crop homogeneity, which results in a dramatic increase in cane yield (Bhullar et al., 2008; da Silva et al., 2020; Kumar et al., 2023b). Additionally, mulching combined with a proper planting method increases soil water availability (Wang et al., 2011).

Due to changes in soil physical properties, soil organic matter decomposes rapidly if it is continuously cultivated for agricultural production, especially in tropical and semiarid regions (Ashagrie et al., 2007), causing soil productivity to decline and soil carbon depletion (Ranjan et al., 2023). It is possible to enhance carbon sequestration and reduce atmospheric CO_2 enrichment by implementing proper input management practices (Paustian et al., 1997; Prosdocimi et al., 2016). Moreover, soil microclimate can be affected by the incorporation of plant residues (Laik et al., 2021).

Considering the above points, it was hypothesized that different planting techniques, mulching, and irrigation scheduling may influence sugarcane growth, yield, and soil properties. Thus, the present study was carried out with the following objectives: (i) to optimize irrigation regime in sugarcane under different planting methods and trash mulching, (ii) to find out the best planting method and trash mulching practice in higher growth, productivity and juice quality of sugarcane under different irrigation schedule, (iii) to assess the short term impact of various planting method with or without trash mulching and irrigation in sugarcane on soil properties, and (iv) to work out the profitability of sugarcane under different planting method and irrigation regime in South Asia.

2 Materials and methods

2.1 Experimental site

The field experiment was carried out during the spring seasons of 2016–17 to 2018–19 at Sugarcane Research Institute

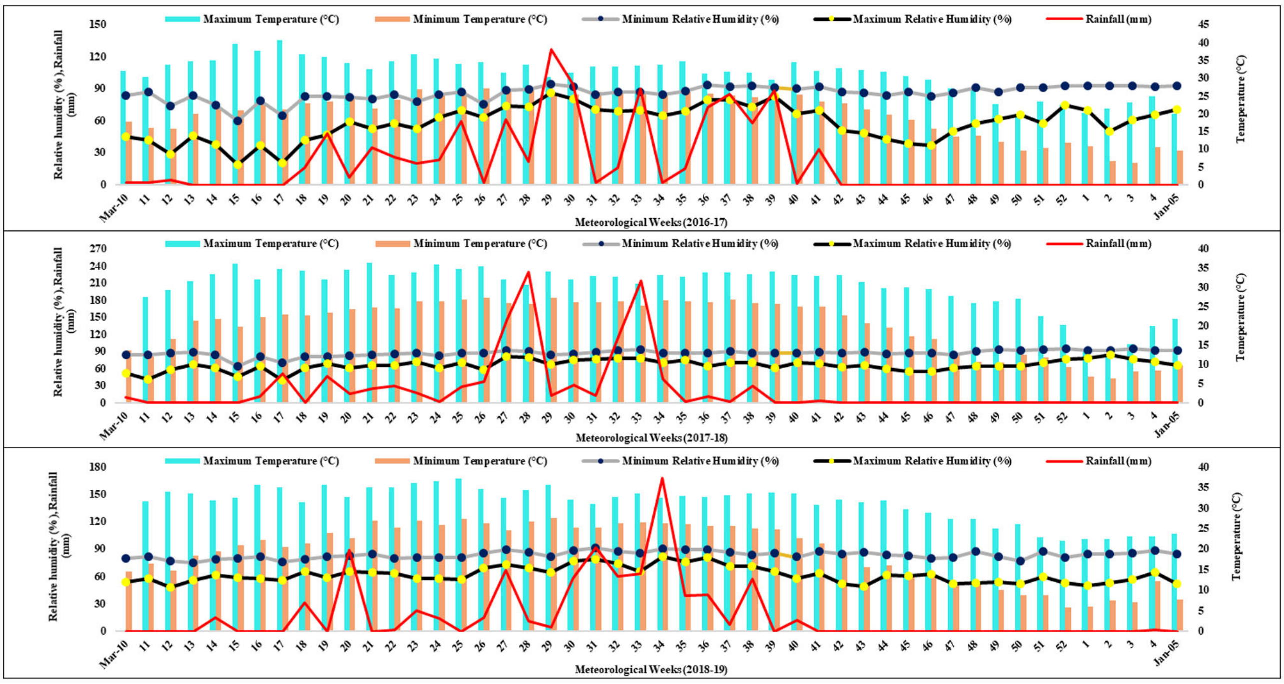

FIGURE 1
The rainfall (mm) and mean weekly maximum relative humidity (%), minimum relative humidity (%), maximum temperature (°C), and minimum temperature (°C), for the (i) 2016–2017, (ii) 2017–2018, and (iii) 2018–2019.

(SRI) farm in Pusa, Bihar, India, with precise coordinates of 85° 40′ E longitude, 25° 59′ N latitude, and 52.1 m above mean sea level. This study was carried out as part of the Project Directorate of ICAR. The study area has a subtropical, hot and humid environment with a mean annual rainfall of 1,210 mm (Supplementary Table 1). Between July and September, 75–80% of the rain occurs. There were significant patterns of rainfall variability during the 3 years of the experiment, both in terms of amount and distribution, raising concerns about the reliability of the EIGP rainfall data. As illustrated in Figure 1, the mean maximum and minimum temperatures, relative humidity, and rainfall during the harvest period are presented. The total rainfall was 1,015.6 mm (2016–17), 1,134.6 mm (2017–18), and 871 mm (2018–19). During the growing year 2016–17, the mean weekly maximum and minimum temperatures ranged from 18.9 to 40.6°C and 6.2 to 27.2°C, respectively. Accordingly, in the year 2018–19, maximum and minimum relative humidity ranged from 75 to 92 and 48 to 82%, respectively.

2.2 Experimental design and treatment details

The experiment was laid out in strip plot design with combinations of four planting methods and three irrigation schedules with three replications. In Table 1, detailed treatment combinations are presented.

TABLE 1 Treatment details of this study.

Treatment	Sugarcane
Planting method with and without mulch	
PM_1	Conventional flat planting (75 cm row spacing) with trash mulching (6 t ha^{-1})
PM_2	Conventional flat planting (75 cm row spacing) without trash mulching
PM_3	Paired row trench planting (30: 120 cm row spacing) with trash mulching (6 t ha^{-1})
PM_4	Paired row trench planting (30: 120 cm spacing) without trash mulching
Irrigation schedule (IW/CPE)	
IS_1	0.60
IS_2	0.80
IS_3	1.00

2.3 Crop management

Prior to cultivation, the experimental site was cleared, plowed, and harrowed manually. The gross plot size was 10 m × 9 m (90 m^2) and the net plot size was 8 × 6 m (48 m^2). Sugarcane variety "CoP 112" was planted on 10, 8, and 5 March during 2016, 2017, and 2018, respectively, using 150,000 buds ha^{-1}. Before planting, the cane setts were treated with chlorpyriphos 20% EC to protect them from insect attack. To supply 150:37.1: 49.8 kg N, P, and K ha^{-1}, diammonium phosphate (DAP), urea, and muriate

TABLE 2 Irrigation requirement, soil moisture contribution, and water requirement of sugarcane (pooled data of three years).

Treatment*	Irrigation requirement		Effective rainfall (cm)	Soil profile moisture contribution (cm)	Water requirement (cm)
	Number	Depth (cm)			
Planting method with and without mulch					
PM_1	3.5	25.8	71.06	1.88	98.78
PM_2	3.5	25.8	71.06	2.00	98.89
PM_3	3.5	25.8	71.06	1.59	98.48
PM_4	3.5	25.8	71.06	1.87	98.76
Irrigation schedule (IW/CPE)					
IS_1	2.7	20.0	71.06	2.03	93.09
IS_2	3.0	22.5	71.06	1.82	95.38
IS_3	4.7	35.0	71.06	1.66	107.7

*Refer to Table 1 for treatment details.

of potash (MOP) were used. To provide a basal dose, half N and full P and K were applied. Sugarcane was top-dressed with remaining N doses in equal splits after the first irrigation and at the maximum tillering stage. In accordance with the treatments, sugarcane trash of 6 t ha^{-1} was applied 50 days after planting. Based on a meteorological approach, irrigation water was scheduled based on a ratio between IW and CPE. To ensure good germination of sugarcane, sufficient moisture conditions were required, and irrigation was applied according to designated irrigation schedules based on a meteorological approach. As a constant depth of irrigation water (75 mm), irrigation was applied to achieve a pre-calculated CPE based on daily evaporation from a USWB Class A open pan. Each plot was irrigated with water measured by water meters. To prevent water from flowing from one plot to another, all plots were separated by double bunds. A conventional flat (CF) planted crop was irrigated throughout, whereas a paired row trench (PT) planted crop was irrigated only in trenches, resulting in a 40% reduction in the wettable area, which is 30 cm (trench) + 30 cm (15 cm + 15 cm both sides of the trench) out of 150 cm of 30:120 cm. To determine the amount of irrigation water applied over the growth season, the depth of water delivered to each treatment plot was multiplied by the total number of irrigations throughout the season. By using the gravimetric method, the moisture content of the soil was determined. The pooled mean of 3 years of number of irrigation, depth, effective rainfall, soil moisture contribution, and water requirement were given in Table 2. Before crop harvesting, irrigation was stopped 20 days in advance.

Water use efficiency (WUE) was estimated as follows (Tayade et al., 2020):

$$WUE\ (kg\ ha^{-1} cm^{-1}) = \frac{Cane\ yield\ (kg/ha)}{Total\ irrigation\ water\ applied\ (cm)}$$

Water productivity is calculated as follows (Das et al., 2018):

$$Waterproductivity\ (Rs\ m^{-3}) = \frac{Gross\ income\ in\ rupees}{Area\ under\ cultivation\ (ha) \times depth\ of\ irrigation\ (m) \times number\ of\ irrigation}$$

In accordance with recommended practices, other agronomic practices *viz.,* weeding, herbicide application and earthing up were followed as required. Sugarcane was harvested on 31st January of 2017, 2018, and 2019, respectively.

2.4 Growth and yield contributing characters

During a 3-year study, biometric observations of the cane growth and yield parameters were recorded, including germination percentage, number of tillers, plant height, millable stalk, single cane weight, and cane yield. In each 8 m long plot, the middle four rows were counted 45 days after planting (DAP) to determine the germination percentage. During 120 DAP, tillers were counted similarly for each plot and presented per hectare. The distance from ground level to the last fully expanded leaf was measured on 10 randomly selected plants from each plot at 240 DAP. Then, their average was calculated for the estimation of plant height.

At harvest, yield contributing characters and yield characteristics were observed. To avoid border effects, cane yield was harvested manually from net plots. For each plot, the cane yield was measured after topping the plants and removing the trash from the stems. In net plots, the number of millable stalks was manually counted and converted to thousands per hectare. During harvesting, 10 randomly stripped canes were collected for measuring cane diameter. By using a vernier caliper, the top, middle, and base of the cane were measured and averaged. From each plot, 10 randomly selected canes were weighed separately, and their respective values were presented as single cane weights. To extract cane juice, 10 randomly selected clean millable canes were crushed in an electric roller cane crusher. According to standard procedures (Meade and Chen, 1977), sucrose % was calculated.

2.5 Soil characteristics and analysis

In this experiment, the soil of the experimental site was sandy loam (Typic Haplustept). Initially, soil samples were pooled

TABLE 3 Initial physicochemical properties of the soil at the study site.

Parameter	Value	Methods used	References
Sand (%)	57.55	Bouyoucos Hydrometer	Piper, 1966
Silt (%)	28.95		
Clay (%)	13.27		
Texture	Sandy loam	Textural Diagram	Black, 1965
Bulk density	1.41 Mg m^{-3}	Core sampler	Black, 1965
Soil pH (1:2.5 soil water suspension)	8.2	Potentiometric	Jackson, 1973
Electrical conductivity	0.32 dS m^{-1}	Potentiometric	Jackson, 1973
Organic carbon	4.9 g kg^{-1}	Walkley and Black method	Nelson and Sommers, 1996
Available nitrogen (N)	227 kg ha^{-1}	Alkaline $KMnO_4$	Subbiah and Asija, 1956
Available phosphorus (P_2O_5)	23 kg ha^{-1}	Olsen's method	Olsen et al., 1954
Available potash (K_2O)	126 kg ha^{-1}	1N neutral ammonium acetate method	Page et al., 1982

TABLE 4 Methods used in soil sample analysis.

Parameters	Methods used	References
Bulk density (Mg m^{-3})	Core sampler	Black, 1965
Organic carbon (g kg^{-1})	Walkley and Black's rapid titration method	Jackson, 1973
Ex-situ soil respiration (mg CO_2-C kg^{-1} soil day^{-1})	Quantities of CO_2-C that are mineralized from unfumigated samples using 30 days incubation at 28 ± 2°C	Page et al., 1982
Soil microbial biomass carbon (SMBC; mg C_{microb} kg^{-1} soil day^{-1})	Chloroform fumigation extraction method	Jenkinson and Ladd, 1981
Dehydrogenase activity (µg TPF g^{-1} 24 hr^{-1})	Triphenly tetrazolium chloride method	Casida et al., 1964

together, and a representative homogeneous sample was drawn and analyzed. At the beginning of the experiment (2016), detailed soil characteristics were determined, and the data are presented in Table 3.

After the harvesting of sugarcane in 2019, samples were taken from the cultivated soil layer at depths of 0–15 cm and collected with a screw sampler from each experimental plot. After drying, powdering, and sieving soil samples through a 2 mm plastic sieve, cloth bags were used to store the soil samples. We analyzed these processed soil samples for the parameters listed in Table 4.

Soil organic carbon stock (Mg ha^{-1}) in 0–15 cm depth = SOC (g kg^{-1}) × 2.22 × BD (Mg m^{-3}).

2.6 Statistical analysis

An analysis of the data from the experiment was performed for each of the 3 years and then pooled together. Statistical Package for Social Sciences (SPSS v. 23.0) software was used for the analysis of variance (ANOVA). *F*-tests at a 5% significance level were used to determine the significance of the treatment effect. Using the critical difference (CD) approach, differences between treatment means were assessed (Gomez and Gomez, 1984).

3 Results

3.1 Growth parameters

Germination percentage and growth attributes are presented in Table 5. The results represent the pooled mean data of the crop of 3 years. Among the planting methods, PT planting (30: 120 cm row spacing) without trash mulching (PM_4) showed a significantly ($p \leq 0.05$) higher germination percentage (37.6%) as compared to CF planting (75 cm row spacing) without mulching (PM_2; 33.3%) and was on par with rest of the planting method and trash management practices at 45 DAP. With regard to irrigation scheduling, IW/CPE ratio of 1.00 (IS_3) had the highest germination percentage (36.7%) accounting for an increase of 6.4% when compared to the IW/CPE of 0.6 (IS_1).

At 120 DAP, PT planting with trash mulching (6 t ha^{-1}; PM_3) produced the highest number of tillers (208,300 ha^{-1}) and was statistically significant ($p \leq 0.05$) over other treatments. CF planting with (PM_1) or without (PM_2) trash mulching resulted in minimum tillers, accounting for 21.1 and 34.6% reduction respectively as compared to the treatment PM_3 (Table 5). Among irrigation schedules, IS_3 treatment recorded the maximum tiller number (215,500 ha^{-1}) which was 47.1 and 16.4% higher as compared to IS_1 and IS_2, respectively.

At 240 DAP, PT planting with trash mulching of 6 t ha^{-1} (PM_3) resulted in the tallest plants which were 18.9, 21.8, and 4.4% higher as compared to CF planting with mulch (PM_1) or without mulch (PM_2) and PT planting without mulch (PM_4), respectively. Similarly, among the different irrigation scheduling, plant height of the crop was significantly higher in IW/CPE ratio of 1.00 (IS_3; 342.1 cm) as compared to IW/CPE ratio of 0.60 (IS_1; 303.4 cm) and at par with the IW/CPE of 0.8 (IS_2; 332.0 cm; Table 5). Hence, IS_3 enhanced plant height to the tune of 11.3% over IS_1.

3.2 Yield attributes and yield

The planting method with or without trash mulching and irrigation regimes had a significant ($p \leq 0.05$) influence on the yield and its attributes, i.e., cane diameter, weight and millable stalk (Table 6). PT planting with trash mulching (6 t ha^{-1}; PM_3) significantly ($p \leq 0.05$) enhanced the cane diameter to the tune of 8.6 and 11.6% over CF planting with mulching and without mulching, respectively. Among the irrigation schedule, the treatment IS_3 recorded a maximum cane diameter (2.41 cm). However, single cane weight was not affected by planting methods with or without trash mulch and different irrigation schedules.

TABLE 5 Growth parameters in sugarcane as affected by planting method and irrigation scheduling (pooled data of 3 years).

Treatment*	Germination percentage at 45 DAP	Tillers ($\times 10^3$ ha^{-1}) at 120 DAP	Plant height (cm) at 240 DAP
Planting method with and without mulch			
PM_1	35.9^a	172.1^c	302.8^c
PM_2	33.3^b	154.9^d	295.7^c
PM_3	36.3^a	208.3^a	360.1^a
PM_4	37.6^a	194.4^b	344.8^b
Irrigation schedule (IW/CPE)			
IS_1	34.5^b	146.5^c	303.4^b
IS_2	36.1^a	185.2^b	332.0^a
IS_3	36.7^a	215.5^a	342.1^a

*See Table 1 for treatment details; statistically significant differences are found in means among columns denoted by different letters at $p \leq 0.05$.

TABLE 6 Yield attributes, yield and sucrose content of sugarcane as influenced by planting methods with or without trash mulching and irrigation schedules (pooled data of 3 years).

Treatment*	Cane diameter (cm)	Single cane weight (g)	Millable stalk ($\times 10^3$ ha^{-1})	Cane yield (t ha^{-1})	Sucrose in juice (%)
Planting method with and without mulch					
PM_1	2.21^b	745.1^a	120.8^b	86.4^b	17.46^a
PM_2	2.15^b	741.3^a	112.7^b	81.7^b	17.55^a
PM_3	2.40^a	765.7^a	140.2^a	103.5^a	17.57^a
PM_4	2.36^a	760.8^a	134.8^a	99.1^a	17.64^a
Irrigation schedule (IW/CPE)					
IS_1	2.14^b	739.2^a	108.5^c	79.2^c	17.40^a
IS_2	2.29^{ab}	756.7^a	129.0^b	94.9^b	17.61^a
IS_3	2.41^a	763.7^a	143.9^a	103.9^a	17.65^a

*See Table 1 for treatment details; statistically significant differences are found in means among columns denoted by different letters at $p \leq 0.05$.

Results showed that the number of millable stalks was highest in the treatment PM_3 which was at par with PM_4 but significantly ($p \leq 0.05$) superior to the treatments of CF planting techniques. This PT planting with trash mulching exhibited about 16.0 and 24.4% increments in millable stalk numbers as compared to the millable stalk numbers under the CF planting method with or without trash mulching, respectively. Moreover, the number of millable stalks was significantly ($p \leq 0.05$) higher for sugarcane irrigated with an IW/CPE of 1.0 (143,900), as compared to crops irrigated with 0.60 and 0.80 IW/CPE schedules.

In sugarcane production, genotype, management techniques, and environment have a major impact on the yield of the crop. By harvesting at the right time of crop maturity, maximum yields and minimal losses can be achieved. The present study indicated that in PT planting with trash mulching of 6 t ha^{-1} (PM_3), cane yield (103.5 t ha^{-1}) was significantly ($p \leq 0.05$) higher compared to CF planting method. The CF planting treatment produced the lowest cane yield (81.7 t ha^{-1}) compared to the other planting methods and trash management practices. Similarly, among the treatment IS_3 (103.9 t ha^{-1}) significantly ($p \leq 0.05$) higher cane yield as compared to other irrigation regime treatments. Furthermore, cane yield was found to be increased by 31.2% and by 9.5% with IW/CPE ratios of 1.00 as compared to treatments with IW/CPE ratios of 0.60 and 0.80 (Table 6). However, juice-quality traits like sucrose content were not significantly ($p \leq 0.05$) influenced by all methods of planting with or without trash mulching and irrigation schedules.

3.3 Water use efficiency and productivity

Based on pooled data for 3 years (Table 7), significantly ($p \leq 0.05$) higher water use efficiency was obtained under PT planting with trash mulching of 6 t/ha (1,049 kg ha^{-1} cm^{-1}) than the PT planting without trash mulching and was statistically as efficient as the other treatments. A similar trend was observed in water productivity. It was also observed that PT planting with trash mulching resulted in the highest water productivity, accounting for an increase of ∼35.9 and 46.6% over the CF planting with or without trash mulching, respectively (Table 1). As well, among the different irrigation scheduling strategies, the highest water use efficiency was associated with IW/CPE of 0.80 (995.4 kg ha^{-1} cm^{-1}) which was comparable to IW/CPE of 1.00 (964.4 kg ha^{-1} cm^{-1}) but significantly higher than IW/CPE of 0.60 ($p \leq 0.05$).

TABLE 7 Water use efficiency, water productivity and economics analysis of sugarcane as influenced by planting methods and irrigation schedules (pooled data of 3 years).

Treatment*	Water- use efficiency (kg ha^{-1} cm^{-1})	Water productivity (Rs m^{-3})	Cost of cultivation ($\times10^3$ Rs ha^{-1})	Net returns ($\times10^3$ Rs ha^{-1})	B/C ratio
Planting method with and without mulch					
PM_1	872.4^{bc}	12.62^{b}	124.8	125.7^{b}	2.01^{b}
PM_2	824.9^{c}	11.70^{b}	120.5	116.6^{b}	1.96^{b}
PM_3	1049.0^{a}	17.15^{a}	130.3	169.9^{a}	2.30^{a}
PM_4	1002.0^{ab}	16.46^{a}	124.0	163.4^{a}	2.31^{a}
Irrigation schedule (IW/CPE)					
IS_1	851.4^{b}	11.50^{b}	122.8	107.1^{c}	1.87^{c}
IS_2	995.4^{a}	15.77^{ab}	124.9	150.4^{b}	2.20^{b}
IS_3	$964.4a^{b}$	16.18^{a}	127.1	174.2^{a}	2.37^{a}

*See Table 1 for treatment details; statistically significant differences are found in means among columns denoted by different letters at $p \leq 0.05$.

Whereas, water productivity was maximum in treatment IS_3 which was 40.7% higher as compared to the treatment IS_1 (Table 7).

3.4 Soil properties

3.4.1 Soil physicochemical parameters

The bulk density under conventional flat planting (75 cm row spacing) with trash mulching of 6 t ha^{-1} and IW/CPE of 1.00 showed the lowest value (1.38, 1.37 Mg m^{-3}), respectively. However, the bulk density of the post-harvest soil was not significantly ($p \leq 0.05$) influenced by the different planting methods and irrigation schedules. Using trash mulching also resulted in a positive trend toward an increase in SOC. In spite of this, SOC was not significantly ($p > 0.05$) impacted by the planting method with or without mulch. The SOC under trash mulching was slightly increased over the 3 years compared to no mulch. Furthermore, SOC also showed significant ($p \leq 0.05$) changes among irrigation scheduling, where a maximum (5.2 g kg^{-1}) was found under the treatment IS_3 and a minimum (4.7 g kg^{-1}) was found in the treatment IS_1 significantly at par with IS_2 (Table 8).

The SOC stock at 0–15 cm soil depth ranged between 15.11 (PM_2) to 16.09 Mg ha $^{-1}$ (PM_3) among the planting method and 15.06 (IS_1) to 15.99 Mg ha^{-1} (IS_3) among the irrigation schedules. However, planting methods with or without trash mulch under different irrigation schedules did not exert significant ($p \leq 0.05$) variation in the SOC stock among all the treatments.

3.4.2 Biological activity

The *ex-situ* soil respiration did not differ significantly between the planting methods. However, *ex-situ* soil respiration was the highest in PT planting with trash mulching of 6 t ha^{-1} (28.42 mg CO_2-C kg^{-1} soil day^{-1}) followed by CF planting with trash mulching (27.38 mg CO_2-C kg^{-1} soil day^{-1}) and the lowest in CF planting without mulch (25.83 mg CO_2-C kg^{-1} soil day^{-1}). Whereas, irrigation schedules significantly influenced the *ex-situ* soil respiration the treatment IS_3 was significantly superior to the treatment IS_1. Moreover, the treatment IS_3, IW/CPE of 1.00 resulted in 12.2 and 6.7% greater rates of *ex-situ* soil respiration as compared to the treatment IS_1 and IS_2, respectively.

As a soil quality indicator, the SMBC is useful for comparing organic matter content across soils in relation to the extent of organic matter accumulation. SMBC is another form of labile carbon and paired row trench planting with trash mulching significantly increased SMBC by 7.5, 12.5, and 12.2% over the treatment PM_1, PM_2, and PM_4, respectively. However, IW/CPE did not exert a significant ($p \leq 0.05$) effect with respect to SMBC. However, among the planting methods, PM_3 recorded significantly highest dehydrogenase activity (255.4 µg TPF g^{-1} 24 h^{-1}) which is statistically comparable with PM_1 (237.7 µg TPF g^{-1} 24 h^{-1}) but superior and 21.1, 17.9% more than PM_2 and PM_4, respectively (Table 8). Furthermore, the increased dehydrogenase activity was noted for the treatment IW/CPE of 0.8 which was at par with IW/CPE of 1.00 but significantly ($p \leq 0.05$) superior to IW/CPE of 0.6 (IS_1).

4 Discussion

4.1 Growth parameters

Growth of sugarcane was found to improve under the PT planting method with or without mulch under IW/CPE of 1.00. There is a possibility that this may be due to optimal sugarcane metabolism (Wang et al., 2013), better soil microclimates that allow for root growth, and other favorable conditions for germination (Singh et al., 2019) in comparison with CF plantings. A better root system contributes to a better swelling and sprouting of cane buds. Similarly, in our study, 0.80 and 1.00 IW/CPE ratios enhanced sugarcane germination by maintaining adequate soil moisture around cane setts. Moisture in the soil is essential for this mechanism. Water infiltration into cells produces turgor pressure, which displaces soil particles, overcomes friction, and allows the plant to extend through the soil (Cole, 1939). As roots grow, their apical meristem undergoes cell division and a zone just

TABLE 8 Bulk density, soil microbial, and dehydrogenase activity as influenced by planting method and irrigation regimes (pooled data of 3 years).

Treatment*	Bulk density (Mg m^{-3})	Soil organic carbon (g kg^{-1})	Soil organic carbon stock (Mg ha^{-1})	*Ex-situ* soil respiration (mg CO_2-C kg^{-1} soil day^{-1})	SMBC (mg C_{microb} kg^{-1} soil day^{-1})	Dehydrogenase activity (µg TPF g^{-1} 24 hr^{-1})
Planting method with and without mulch						
PM_1	1.38^{a}	5.1^{a}	15.86^{a}	27.38^{a}	174.53^{bc}	237.7^{ab}
PM_2	1.41^{a}	4.8^{a}	15.11^{a}	25.83^{a}	166.76^{c}	210.8^{c}
PM_3	1.39^{a}	5.2^{a}	16.09^{a}	28.42^{a}	187.62^{a}	255.4^{a}
PM_4	1.42^{a}	4.9^{a}	15.60^{a}	26.10^{a}	167.27^{c}	216.5^{bc}
Irrigation schedule (IW/CPE)						
IS_1	1.43^{a}	4.7^{b}	15.06^{a}	25.45^{b}	172.20^{a}	216.7^{b}
IS_2	1.40^{a}	5.1^{a}	15.94^{a}	26.78^{ab}	175.03^{a}	242.4^{a}
IS_3	1.37^{a}	5.2^{a}	15.99^{a}	28.57^{a}	174.91^{a}	231.2^{ab}

*See Table 1 for treatment details; statistically significant differences are found in means among columns denoted by different letters at $p \leq 0.05$.

behind their apex undergoes cell expansion. Root development and germination are therefore dependent on a proper soil moisture regime (Clark et al., 2003; Singh et al., 2022). High daytime temperatures are associated with water stress leading to low growth, high tiller mortality, and low cane yields. However, in our study, planting method and irrigation schedules significantly impacted the tillers at 120 DAP and paired row planting (30:120 cm) row spacing with trash mulching @ 6 t ha^{-1} produced a higher number of tillers and it was increased by 34.5% than conventional flat planting without mulching this might be due to the reason that paired row planting provided adequate aeration, water and nutrients for the roots, resulting into a greater number of tillers. In addition, trash mulch application may serve to retain water in the rhizosphere for a longer period, thereby retaining soil moisture. According to Singh (2012), PT planting at 105 DAP showed significantly higher tiller counts than furrow-irrigated raised beds. Furthermore, Wiedenfeld and Enciso (2008) report that irrigation water increases soil water potential and the ability of the roots to absorb water, thus controlling hydric balance. Optimal hydrological balance helps maintain stomatal conductance and photosynthetic activity in plants. Furthermore, Kumar et al. (2013) and Dingre and Gorantiwar (2021) found that water use is related to the crop growth demand and soil aeration improves the speed of cell division and elongation. Hence, due to irrigation schedules, the difference in water led to significant variability in plant height.

4.2 Yield attributes and yield

There was a significant reduction in cane yield with deficit irrigation, showing that water quantity has a direct impact on cane yield. Further, cane yield is directly proportional to water transpiration (Tayade et al., 2020). In this regard, it is necessary to maintain good soil moisture throughout the various growth stages of sugarcane (Dhanapal et al., 2019). In general, it is believed that PT plantings with IW/CPE of 1.00 have higher yield attributes than CF ones with IW/CPE of 0.6 based on factors such as the number of millable stalks, the cane diameter, and the weight of each cane. There may have been an improvement in microclimate conditions as well as less competition for resources in the crop during reproductive stages as a result of better sprouting and tillering of the crop under frequent watering under PT planting with trash mulching under IW/CPE 1.00, which leads to greater cane diameter (Nadeem et al., 2020). As a result of PT planting, synchronized tillers were able to form in this study, which may have facilitated improved soil water conservation, a cooler soil environment, and effective weed control. Adding trash mulch at these rates resulted in significant yield increases in canes that were thicker, heavier, and more desirable in terms of quality. Consistent with our results, Singh and Brar (2015) also reported that paired row trench planting recorded the highest cane diameter, cane weight, and millable stalks. This investigation found that the application of trash as the mulch of (6 t ha^{-1}) could not improve the cane yield significantly as compared to trash mulching in the PT planting system. In contrast, Concenco et al. (2016) and Bassey et al. (2021) found that trash mulch application of 6–9 t ha^{-1} produced taller plants, thicker cane stalks, higher brix content of sugarcane and higher cane yield. Moreover, Kumar et al. (2015) reported that the tallest plants, maximum tillers, millable canes, average cane weight, and cane yield were observed when trash mulch was applied at 10 t ha^{-1}. This investigation found that irrigation scheduling at an IW/CPE ratio of 1.00 resulted in maximum cane yield. In such circumstances, soil moisture might reach an optimum level during growth periods, leading to better leaf area expansion and photosynthesis, resulting in increased plant growth. A similar observation has been made by Singh and Brar (2015), who also reported a higher yield for crops irrigated at 1.0 IW: CPE than those irrigated at 0.75 and 0.50. Whereas, a significant increase in cane yield was reported by Singh et al. (2007) and Singh (2012) when irrigation scheduling for IW/CPE ratios of 0.75 over 0.50 was used. Moreover, 56% cane yield reduction due to irrigation at 50% CPE as compared to 100% CPE had been reported by Vasantha et al. (2020). In PT plantings with an IW/CPE of 1.00, trash application significantly affected the millable stalks by affecting the emergence and tillering patterns and, in turn, the yield of sugarcane, since it affected the diameter and weight of the canes at a later stage. Whereas, green cane trash blanket reduced the soil temperature and its variability as compared to the bare soil treatment; but did not show difference in evapotranspiration, soil moisture, and growth attributes of sugarcane (Gonçalves et al., 2023).

4.3 Water use efficiency and productivity

In this study, we have observed higher water use efficiency and water productivity with trash mulching with an irrigation schedule of 1.00 over non-mulching with IW/CPE of 0.6 and 0.8. This was due to a reduction in irrigation water losses through percolation and evaporation. Increasing yield and reducing irrigation water usage increases water use efficiency and productivity. Similar results findings given by Banerjee et al. (2016). Earlier studies showed that under mulched PT planting, water use efficiency, and water productivity were greater than under no-mulch planting, demonstrating the effectiveness of mulch in reducing soil evaporation and increasing plant respiration (Zhao et al., 1996; Zhang et al., 1999). With an increase in irrigation water applied, water use efficiency decreased, but water productivity increased (Singh and Mohan, 1994; Zhang X. Y. et al., 2005; Singh et al., 2007). The results from our study indicate that surface retention of crop residues reduces water requirements by conserving soil moisture through reduced evaporation losses (Jat et al., 2015; Sandhu et al., 2019). In our study, an increment in water productivity was observed and the increment was 28.9% under IS_3 (IW/CPE: 1.0) over IS_1 (IW/CPE: 0.60). The increase in irrigation amount may lead to a more efficient utilization of light and heat (Zou et al., 2020), resulting in a higher yield. Conversely, an excessive supply of water can result in an excessive use of light and heat, as well as an extended period of vegetative growth and a delayed period of reproductive growth. In addition, excessive irrigation may have caused some deep drainage and leaching of soil nutrients, which resulted in decreased sugarcane production (Fan et al., 2018).

The ultimate goal of agriculture is to maximize economic benefits. It is thus expected that paired row trench planting with trash mulching under IW/CPE of 1.00 should result in increased net returns and B/C ratio because of enhanced cane yield (Showler, 2023) and the results of the present study confirm this. Similarly, as compared to conventional planting of sugarcane, paired-row trench planting showed 34.0% higher returns (Singh and Brar, 2015), while 120 cm PT planting with lentils as intercrop yielded a maximum net return of Rs. 321,254 ha^{-1} (Nadeem et al., 2020).

4.4 Soil properties

The findings of the current investigation showed that the SOC dynamics under different planting methods with trash mulch applications under various irrigation schedules differed significantly. The amount of SOC in post-harvest soil is dependent on the rate of organic matter decomposition and the addition of residual biomass (Yadav et al., 2009). Trash mulch can improve soil organic carbon and consequently improve soil health for longer periods under CF planting or PT planting (Shukla and Yadav, 2011). In contrast, Preet et al. (2022) found that soil organic carbon was slightly decreased with mulching. Nevertheless, Lal (1997) observed that mulching crop residue increased carbon accumulation on clayey Oxisol by 15% after 6 years, which represents 0.65 Mg of C ha^{-1} $year^{-1}$ and 14% of mulched carbon. Further, residue retention under a cereal-based cropping system contributed significantly to an increase in SOC stock at 0–30 cm soil depth in South Asia (Chatterjee et al., 2018; Das et al., 2018).

Under planting methods with or without mulching-irrigation modulated conditions, soil enzyme activity may be altered, resulting in alterations in soil characteristics. In this study, it was observed that trash mulching enhances decomposition by altering moisture content, enhancing heat in the topsoil, and stimulating microbial activity. In these treatments, higher soil microbial activities might have resulted from increased moisture leading to fresh residue being added by root biomass, which has boosted soil respiration with irrigation. Alternatively, sugarcane trash could allow nutrients and carbon to slowly release as required by the crop, resulting in reduced losses and a soil C pool that builds over time (Yadav et al., 1994; Sparling et al., 1998). The experimental results revealed that the plots under trash mulching with PT planting accumulate more soil C and, thereby could be reckoned to promote the C sequestration potential of soil (Shukla et al., 2013). Earlier research has shown that organic mulches increase soil organic carbon levels significantly (Saroa and Lal, 2003), with an increase of 33.0% over 10 years (Blanco-Canqui and Lal, 2007). Surendran et al. (2016) found that trash shredding with composted pressmud and application of microbial consortia resulted in higher soil microbial biomass carbon which increased soil available nutrients under a sugarcane planting system. In calcareous arid and semiarid soils with a low percentage of organic matter, mulching materials have been reported to improve soil microbial activity (Khadem and Raiesi, 2017; Mubarak et al., 2021). However, dehydrogenase activity is associated with intact cells of microorganisms and is thought to represent the range of oxidative activities of soil microorganisms (Pramanick et al., 2022). This research suggests that trash mulching in the PT planting might provide a conducive environment for microbe growth, which would increase soil enzyme activity. When soil moisture is adequate, high soil dehydrogenase activity may be achieved because microorganisms develop more rapidly in soil conditions with good oxygen (Stepniewska and Wolinska, 2005; Borowik and Wyszkowska, 2016).

In addition, a significant increase in SOC was observed due to an increase in root biomass due to a positive relationship between SOC dynamics and long-term residue mulching (Maharana et al., 2012; Liu et al., 2014). Moreover, organic carbon content and microbial activity in surface soil increased significantly due to the application of optimum moisture under suitable planting methods helped in increasing biomass production (Tank and Patel, 2013). Accordingly, the complementary effect of trash mulching of 6 t ha^{-1} with PT planting and irrigation at IW/CPE of 1.00 could be considered a significant practice for raising and sustaining sugarcane productivity as well as soil health.

5 Conclusions

Since sugarcane is a wide-spaced crop, irrigation applications to the entire field require a large amount of water. However, water supplies are becoming increasingly scarce. Irrigation methods that save water are increasingly advocated and yet other aspects are neglected, especially irrigation scheduling. Furthermore, farmers have lack of knowledge of standard planting methods and the benefits of trash mulching in sugarcane. Therefore, it is necessary to generate knowledge of planting methods with or without trash mulching, and irrigation scheduling, and this study specifically focuses on this. This study indicates that PT planting and mulching (6 t ha^{-1}) under IW/CPE of 1.00 resulted in better germination and vigor of the crop, resulting in enhanced yield attributes which increased cane yield by 26.7% and net monetary return by 35.2% respectively as compared to CF planting. Increased plant growth parameters due to different planting methods and irrigation schedules presented a higher correlation with cane yield. The crop should be irrigated at 0.8 or 1.00 IW/CPE for higher water productivity and water-use efficiency in sugarcane. Furthermore, there was an increase of 6.5% in the SOC in PT planting with trash as compared to CF planting without trash. Similarly, SMBC and dehydrogenase activity increased due to different planting methods with trash mulch, and irrigation scheduling. SOC and biological properties of the soil are significantly positively correlated with cane yield. Therefore, irrigating sugarcane with IW/CPE of 1.00 in paired row trench (PT) planting technique (30:120 cm) with mulch of 6 t ha^{-1} is the best planting system in sugarcane to attain higher crop yield, water productivity, soil quality, and higher B/C ratio in sugarcane especially in this agroecology of South Asia.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

NK: Conceptualization, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. SSo: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft. LR: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft. VK: Conceptualization, Investigation, Methodology, Validation, Visualization, Writing – original draft. JK: Conceptualization, Formal analysis, Methodology, Validation, Visualization, Writing – original draft. BP: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AS: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AH: Data curation, Formal analysis, Funding acquisition, Software, Writing – review & editing. LA: Data curation, Formal analysis, Funding acquisition, Project administration, Software, Writing – review & editing. SSa: Data curation, Formal analysis, Funding acquisition, Software, Writing – review & editing. AG: Data curation, Formal analysis, Funding acquisition, Software, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1340551/full#supplementary-material

References

Ahmad, Q. A., Moors, E., Biemans, H., Shaheen, N., Masih, I., and Hashmi, M. Z. R. (2023). Climate-induced shifts in irrigation water demand and supply during sensitive crop growth phases in South Asia. *Clim. Change* 176:150. doi: 10.1007/s10584-023-03629-7

Aquino, G. S., Costa, M., Shahab, D. C. M., Medina, C. C., and Santiago, A. D. (2017). Sugarcane straw management and its impact on production and development of ratoons. *Industr. Crops Product.* 102, 58–64. doi: 10.1016/j.indcrop.2017.03.018

Ashagrie, Y., Zech, W., Guggenberger, G., and Mamo, T. (2007). Soil aggregation and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. *Soil Till. Res.* 94, 101–108. doi: 10.1016/j.still.2006.07.005

Banerjee, H., Puste, A. M., Ray, K., Sarkar, S., Chakraborty, A., and Rana, L. (2016). Influence of irrigation levels and mulching on growth, water use, yield, economics and quality of potato (*Solanum tuberosum*) under new alluvial soil of West Bengal. *Ind. J. Agron.* 61, 377–383. doi: 10.59797/ija.v61i3.4378

Bassey, M. S., Kolo, M. G. M., Daniya, E., and Odofin, A. J. (2021). Trash mulch and weed management practice impact on some soil properties, weed dynamics and sugarcane (*Saccharum officinarum* L.) genotypes plant crop productivity. *Sugar Tech.* 23, 395–406. doi: 10.1007/s12355-020-00899-8

Bhullar, M. S., Thind, K. S., Uppal, S., and Singh, K. (2008). Productivity, profitability and quality of sugarcane (*Saccharum* spp) plant ratoon system in relation to planting methods and seeding rate. *Ind. J. Agron.* 53, 195–199. doi: 10.59797/ija.v53i3.4859

Black, C. A. (1965). *Methods of Soil Analysis, Part 1 and 2. Agronomy Monograph no. 3 in the series "Agronomy."* (Madison, WI: American Soc. Agron., Inc.), 148.

Blanco-Canqui, H., and Lal, R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil Till. Res.* 95, 240–254. doi: 10.1016/j.still.2007.01.004

Borowik, A., and Wyszkowska, J. (2016). Soil moisture as a factor affecting the microbiological and biochemical activity of soil. *Plant Soil Environ.* 62, 250–255. doi: 10.17221/158/2016-PSE

Braunbeck, O. A., and Magalhaes, P. S. G. (2010). "Technological evaluation of mechanization of sugarcane," in *Bioethanol from Sugarcane: R & D to Productivity and Sustainability*, ed. L. A. B. Cortez (Sáo Paulo: Blucher), 556.

Casida, L. E., Klein, D. A., and Santoro, T. (1964). Soil dehydrogenase activity. *Soil Sci.* 98, 371–376. doi: 10.1097/00010694-196412000-00004

Chatterjee, S., Bandyopadhyay, K. K., Pradhan, S., Singh, R., and Datta, S. P. (2018). Effects of irrigation, crop residue mulch and nitrogen management in maize (*Zea mays* L.) on soil carbon pools in a sandy loam soil of Indo-Gangetic plain Region. *Catena* 165, 207–216. doi: 10.1016/j.catena.2018.02.005

Clark, L. J., Whalley, W. R., and Baraclough, P. B. (2003). How do roots penetrate strong soil? *Plant Soil* 255, 93–104. doi: 10.1023/A:1026140122848

Cole, R. C. (1939). Soil macro-structure as affected by cultural treatments. *Hilgardia* 12, 427–472. doi: 10.3733/hilg.v12n06p427

Concenco, G., Lemefilho, J. R. A., Silva, C. J., Marques, R. F., Silva, L. B. X., and Correia, I. V. T. (2016). Weed occurrence in sugarcane as function of variety and ground straw management. *Planta Daninha* 34, 219–228. doi: 10.1590/S0100-83582016340200003

da Silva, M. T., Martinazzo, R., Silva, S. D. A., Bamberg, A. L., Stumpf, L., Fermino, M. H., et al. (2020). Innovative substrates for sugarcane seedling production: sewage sludges and rice husk ash in a waste-to-product strategy. *Industr. Crops Prod.* 157:112812. doi: 10.1016/j.indcrop.2020.112812

Dalin, C., Wada, Y., Kastner, T., and Puma, M. J. (2017). Groundwater depletion embedded in international food trade. *Nature* 543, 700–704. doi: 10.1038/nature21403

Dangar, S., Asoka, A., and Mishra, V. (2021). Causes and implications of groundwater depletion in India: a review. *J. Hydrol.* 596:126103. doi: 10.1016/j.jhydrol.2021.126103

Das, T. K., Sahrawat, Y. S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K. K., Sharma, A. R., et al. (2018). Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crop Res.* 215, 222–231. doi: 10.1016/j.fcr.2017.10.021

Denmead, O. T., Mayocchi, C. L., and Dunin, F. X. (1997). Does green cane harvesting conserve soil water? *Proc. Conf. Austral. Soc. Sugar Technol.* 19, 139–146.

Dhanapal, R., Tayade, A. S., Bhaskaran, A., and Geetha, P. (2019). Efficient water management in sugarcane with composted coir pith and sugarcane trash under tropical Indian conditions. *Sugar Tech.* 21, 256–264. doi: 10.1007/s12355-018-0593-3

Dingre, S. K., and Gorantiwar, S. D. (2021). Soil moisture based deficit irrigation management for sugarcane (*Saccharum officinarum* L.) in semiarid environment. *Agricult. Water Manag.* 245:106549. doi: 10.1016/j.agwat.2020.106549

Fan, J., Yue, W., Wu, L., Zhang, F., Cai, H., Wang, X., et al. (2018). Evaluation of SVM, ELM and four tree-based ensemble models for predicting daily reference evapotranspiration using limited meteorological data in different climates of China. *Agricult. For. Meteorol.* 263, 225–241. doi: 10.1016/j.agrformet.2018.08.019

Gan, Y. T., Campbell, C. A., Liu, L., Basnyat, P., and McDonald, C. L. (2009). Water use and distribution profile under pulse and oilseed crops in semiarid northern high latitude areas. *Agric. Water Manage.* 96, 337–348. doi: 10.1016/j.agwat.2008.08.012

Gomez, K. A., and Gomez, A. A. (1984). *Statistical Procedures for Agricultural Research*. Hoboken, NJ: John Wiley & Sons.

Gonçalves, I. Z., Vianna, M. S., Nassif, D. S. P., Carvalho, K., and Marin, F. R. (2023). Effects of residue from harvested green cane on evapotranspiration, growth, and development of irrigated sugarcane in southern Brazil. *Sugar Tech.* 25, 1445–1455. doi: 10.1007/s12355-023-01308-6

Jackson, M. L. (1973). *Soil Chemical Analysis*. New Delhi: Prentice Hall of India Pvt. Ltd.

Jat, H. S., Singh, G., Singh, R., Choudhary, M., Jat, M. L., Gathala, M. K., et al. (2015). Management influence on maize-wheat system performance, water productivity and soil biology. *Soil Use Manag.* 31, 534–543. doi: 10.1111/sum.12208

Jenkinson, D. S., and Ladd, J. N. (1981). "Microbial biomass in soil," in *Soil Biochemistry, Vol 5*, eds. E. A. Paul and J. N. Ladd (New York, NY: Marcel Dekker), 1.

Jiang, R., Li, X., Zhou, M., Li, H. J., Zhao, Y., Yi, J., et al. (2016). Plastic film mulching on soil water and maize (*Zea mays* L.) yield in a ridge cultivation system on Loess Plateau of China. *Soil Sci. Plant Nutr.* 62, 1–12, doi: 10.1080/00380768.2015.1104642

Khadem, A., and Raiesi, F. (2017). Responses of microbial performance and community to corn biochar in calcareous sandy and clayey soils. *Appl. Soil Ecol.* 114, 16–27. doi: 10.1016/j.apsoil.2017.02.018

Kingston, G., Donzelli, J. L., Meyer, J. H., Richard, E. P., Ruttun, S. S., Torres, J., et al. (2005). Impact of green cane harvest and production system on the agronomy of sugarcane. *Proc. Int. Soc. Sugar Cane Technol.* 25, 184–190.

Kumar, N., Rana, L., Singh, A. K., Pramanick, B., Gaber, A., Alsuhaibani, A. M., et al. (2023a). Precise macronutrient application can improve cane yield and nutrient uptake in widely spaced plant-ratoon cycles in the Indo-Gangetic plains of India. *Front. Sustain. Food Syst.* 7:1223881. doi: 10.3389/fsufs.2023.1223881

Kumar, N., Singh, H., Kumar, V., and Singh, V. P. (2013). Productivity and water-use efficiency of spring-planted sugarcane (*Saccharum* sp. hybrid complex) under various planting methods and irrigation regimes. *Ind. J. Agron.* 58, 592–596. doi: 10.59797/ija.v58i4.4244

Kumar, N., Sow, S., Rana, L., Singh, A. K., Kumar, A., Kumar, A., et al. (2023b). Physio-agronomic performance of sugarcane (*Saccharum* spp. hybrid complex) genotypes under various planting geometry. *Ann. Agri. Res.* 44, 93–98. doi: 10.2139/ssrn.4667946

Kumar, S., Chand, G., Mandal, D., Kumar, A., and Kumar, S. (2015). Effect of trash mulching on quantitative and qualitative parameters of sugarcane. *Ecol. Environ. Conserv.* 21, 141–143.

Laik, R., Singh, S. K., Pramanick, B., Kumari, V., Nath, D., Dessoky, E. S., et al. (2021). Improved method of boron fertilization in rice (*Oryza sativa* L.)-mustard (*Brassica juncea* L.) cropping system in upland calcareous soils. *Sustainability* 13:5037. doi: 10.3390/su13095037

Lal, R. (1997). Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2 enrichment. *Soil Till. Res.* 43, 81–107. doi: 10.1016/S0167-1987(97)00036-6

Liu, J., Bu, L., and Zhu, L. (2014). Optimizing plant density and plastic film mulch to increase maize productivity and Water-Use efficiency in semiarid areas. *Agron. J.* 106, 1138–1146. doi: 10.2134/agronj13.0582

Maharana, P. C., Sharma, B. M., Biswas, D. R., Dwivedi, B. S., and Singh, R. V. (2012). Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet-wheat cropping system in an Inceptisol of subtropical India. *Field Crop Res.* 136, 32–41. doi: 10.1016/j.fcr.2012.07.002

Meade, G. P., and Chen, G. C. P. (1977). *Cane Sugar Handbook, 10th Edn*. (New York, NY: John Willey and Sons), 882–885.

Mubarak, M., Salem, E. M. M., Kenawey, M. K. M., and Saudy, H. S. (2021). Changes in calcareous soil activity, nutrient availability, and corn productivity due to the integrated effect of straw mulch and irrigation regimes. *J. Soil Sci. Plant Nutr.* 21, 2020–2031. doi: 10.1007/s42729-021-00498-w

Nadeem, M., Tanveer, A., Sandhu, H., Javed, S., Safdar, M. E., Ibrahim, M., et al. (2020). Agronomic and economic evaluation of autumn planted sugarcane under different planting patterns with lentil intercropping. *Agronomy* 10:644. doi: 10.3390/agronomy10050644

Nelson, D. W., and Sommers, L. E. (1996). "Total carbon, organic carbon and organic matter," in *Methods of Soil Analysis. Part 3 - Chemical Methods*, eds. D. L.

Sparks, A. L. Page, P. A. Helmke, R. H. Loeppert, P. N., Soltanpour, M. A. Tabatabai, et al. (Madison, WI: SSSA), 961–1010.

Olsen, S. R., Cole, C. V., and Watanabe, F. S. (1954). *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circular No. 939*. Washington, DC: US Government Printing Office.

Page, A. L., Miller, R. H., and Keeney, D. R. (1982). *Methods of Soil Analysis. Part 2 - Chemical and Microbiological Properties*. Madison, WI: American ASA.

Paustian, K., Collins, H. P., and Paul, E. A. (1997). "Management control on soil carbon," in *Soil Organic Matter in Temperate Agro Ecosystems, Long Term Experiments in North America*. eds E. A. Paul, K. Paustian, E. T. Elliott, C. V. Cole (New York, NY: CRC Press), 15–49.

Piper, C. S. (1966). *Soil and Plant Analysis*. (New York, NY: Academic Press), 47–77.

Pramanick, B., Kumar, M., Naik, B. M., Kumar, M., Singh, S. K., Maitra, S., et al. (2022). Long-term conservation tillage and precision nutrient management in maize-wheat cropping system: effect on soil properties, crop production, and economics. *Agronomy* 12:2766. doi: 10.3390/agronomy12112766

Pramanick, B., Mahapatra, B. S., Datta, D., Dey, P., Singh, S. P., Kumar, A., et al. (2023). An innovative approach to improve oil production and quality of mustard (*Brassica juncea* L.) with multi-nutrient-rich polyhalite. *Heliyon* 9:e13997. doi: 10.1016/j.heliyon.2023.e13997

Preet, M. S., Kumar, R., Valipour, M., Singh, V. P., Neha, A., Singh, A. K., et al. (2022). Soil nutrient status and morphometric responses of guava under drip irrigation and high-tech horticultural techniques for sustainable farming. *Hydrology* 9:151. doi: 10.3390/hydrology9090151

Prosdocimi, M., Tarolli, P., and Cerdà, A. (2016). Mulching practices for reducing soil water erosion: a review. *Earth-Sci. Rev.* 161, 191–203. doi: 10.1016/j.earscirev.2016.08.006

Rajput, J., Kothari, M., Bhakar, S. R., Dimple., Kushwaha, N. L., Singh,. P. K., et al. (2022). Evaluation of water delivery performance of right main canal of Bhimsagar medium irrigation scheme, Rajasthan. *ISH J. Hydraul. Eng.* 2022:2066483. doi: 10.1080/09715010.2022.2066483

Ranjan, S., Kumar, S., Dutta, S. K., Sow, S., Kumar, S., and Sushant. (2023). Long-term organic amendment application improves soil fertility status, nutrient accumulation and crop productivity under rice-wheat cropping system. *Commun. Soil Sci. Plant Anal.* 2023:2227240. doi: 10.1080/00103624.2023.2227240

Sandhu, O. S., Gupta, R. K., Thind, H. S., Jat, M. L., and Sidhu, H. S. (2019). Drip irrigation and nitrogen management for improving crop yields, nitrogen use efficiency and water productivity of maize-wheat system on permanent beds in north-west India. *Agri. Water Manag.* 219, 19–26. doi: 10.1016/j.agwat.2019.03.040

Saroa, G. S., and Lal, R. (2003). Soil restorative effects of mulching on aggregation and carbon sequestration in Miamian soil in Central Ohio. *Land Degrad. Dev*. 14, 481–493. doi: 10.1002/ldr.569

Showler, A. T. (2023). Mulched and soil-incorporated sugarcane greenchop residue and compost: effects on selected soil components, sugarcane nutrients, Mexican rice borer injury, and yield. *Environ. Syst. Res.* 12, 1–12. doi: 10.1186/s40068-023-00284-w

Shukla, S. K., Lal, M., and Singh, S. K. (2013). Improving bud sprouting, growth and yield of winter initiated sugarcane ratoon through tillage cum organic mediated rhizospheric modulation in Udic ustochrept under subtropical Indian condition. *Soil Till. Res.* 126, 50–59. doi: 10.1016/j.still.2012.07.016

Shukla, S. K., and Yadav, R. L. (2011). Improving growth and yield of winter initiated sugarcane (*Saccharum* spp. hybrid complex) ratoon through bioagents amended pressmud cake in sub-tropical India. *Ind. J. Agri. Sci.* 81, 1184–1186.

Singh, I. (2012). Optimizing irrigation schedule in sugarcane (*Saccharum* spp. hybrid complex) under different planting methods in sub-tropical India. *Ind. J. Sugarcane Technol.* 27, 68–72.

Singh, K., and Brar, A. S. (2015). Effect of planting methods and irrigation schedules on cane yield, quality, economics and water productivity of spring sugarcane (*Saccharum officinarum*) in South Western Punjab. *Ind. J. Agron.* 60, 601–605. doi: 10.59797/ija.v60i4.4500

Singh, K., Pal, R., Chalotra, N., and Brar, A. S. (2022). Water productivity of sugarcane influenced by planting techniques, mulching and irrigation scheduling in indo-gangetic plains of India. *Sugar Tech.* 24, 408–418. doi: 10.1007/s12355-021-01041-y

Singh, P., Singh, S. N., Tiwari, A. K., Pathak, S. K., Singh, A. K., Srivastava, S., et al. (2019). Integration of sugarcane production technologies for enhanced cane and sugar productivity targeting to increase farmers' income: strategies and prospects. *3 Biotech.* 9:48. doi: 10.1007/s13205-019-1568-0

Singh, P. N., and Mohan, S. C. (1994). Water use and yield response of sugarcane under different irrigation schedules and nitrogen levels in a subtropical region. *Agri. Water Manag.* 26, 253–264. doi: 10.1016/0378-3774(94)90012-4

Singh, P. N., Shukla, S. K., and Bhatnagar, V. K. (2007). Optimizing soil moisture regime to increase water use efficiency of sugarcane (*Saccharum* spp. hybrid complex) in subtropical India. *Agri. Water Manag.* 90, 95–100. doi: 10.1016/j.agwat.2007.02.008

Singh, S. P., Mahapatra, B. S., Pramanick, B., and Yadav, V. R. (2021). Effect of irrigation levels, planting methods and mulching on nutrient uptake, yield, quality, water and fertilizer productivity of field mustard (*Brassica rapa* L.) under sandy loam soil. *Agri. Water Manag.* 244:106539. doi: 10.1016/j.agwat.2020.106539

Sparling, G. P., Schipper, L. A., McLeod, M., Basher, L., and Rijkse, W. (1998). *Trialing Soil Quality Indicators for State of the Environment Monitoring. Research Report 1997/1998*. Lincoln: Unpublished Landcare Research Contract Report LC9798/141 for the Sustainable Management Fund, Ministry for the Environment Project 5001, Landcare Research.

Stepniewska, Z., and Wolinska, A. (2005). Soil dehydrogenase activity in the presence of chromium (III) and (VI). *Int. Agrophys*. 19, 79–83.

Subbiah, B., and Asija, G. L. (1956). A rapid procedure for estimation of available nitrogen in soils. *Curr. Sci.* 25, 259–260.

Sulaiman, M., Abdulsalam, Z., and Damisa, M. A. (2015). Profitability of sugarcane production and its contribution to farm income of farmers in Kaduna State, Nigeria. *Asian J. Agri. Extens. Econ. Sociol.* 7, 1–9. doi: 10.9734/AJAEES/2015/18987

Surendran, U., Ramesh, V., Jayakumar, M., Marimuthu, S., and Sridevi, G. (2016). Improved sugarcane productivity with tillage and trash management practices in semi-arid tropical agroecosystem in India. *Soil Till. Res.* 158, 10–21. doi: 10.1016/j.still.2015.10.009

Tank, R. V., and Patel, N. L. (2013). Influence of fertigation on yield and nutrient status in soil and leaf of papaya (*Carica papaya* L.) var. Madhu Bindu under south Gujarat condition. *Asian J. Hortic.* 8, 170–173.

Tayade, A. S., Vasantha, S., Anusha, S., Kumar, R., and Hemaprabha, G. (2020). Irrigation water use efficiency and water productivity of commercial sugarcane hybrids under water-limited conditions. *Trans. ASABE* 63, 125–132. doi: 10.13031/trans.13548

Turner, N. C., and Meyer, R. (2011). "Synthesis of regional impacts and global agricultural adjustments," in *Crop Adaptation to Climate Change*, eds. S. S. Yadav,. R. J. Redden, J. L. Hatfield, H. Lotze-Campen, A. E. Hall (Chichester: Wiley/Blackwell), 156–165.

Vasantha, S., Tayade, A. S., Anusha, S., Geetha, P., and Hemaprabha, G. (2020). Physiological efficiency of sugarcane clones under water-limited conditions. *Trans. ASABE* 63, 133–140. doi: 10.13031/trans.13550

Wang, M., Zheng, Q., Shen, Q., and Guo, S. (2013). The critical role of potassium in plant stress response. *Int. J. Mol. Sci.* 14, 7370–7390. doi: 10.3390/ijms14047370

Wang, T. C., Wei, L., Wang, H. Z., Ma, S. C., and Ma, B. L. (2011). Responses of rainwater conservation, precipitation-use efficiency and grain yield of summer maize to a furrow planting and straw-mulching system in northern China. *Field Crops Res*. 124, 223–230. doi: 10.1016/j.fcr.2011.06.014

Wiedenfeld, B., and Enciso, J. (2008). Sugarcane responses to irrigation and nitrogen in semiarid South Texas. *Agron. J.* 100, 665–671. doi: 10.2134/agronj2007.0286

Wiedenfeld, R. P. (2000). Water stress during different sugarcane growth periods on yield and response to N fertilization. *Agri. Water Manag.* 43, 173–182. doi: 10.1016/S0378-3774(99)00053-0

Yadav, R. L., Prasad, S. R., Singh, R. P., and Srivastava, V. K. (1994). Recycling sugarcane trash to conserve soil organic carbon for sustaining yields of successive ratoon crops in sugarcane. *Bioresour. Technol.y* 49, 231–235. doi: 10.1016/0960-8524(94)90045-0

Yadav, R. L., Shukla, S. K., Suman, A., and Singh, P. N. (2009). Trichoderma inoculation and trash management effects on soil microbial biomass, soil respiration, nutrient uptake and yield of ratoon sugarcane under subtropical conditions. *Biol. Fertil. Soils* 45, 461–468. doi: 10.1007/s00374-009-0352-4

Yang, X., Soothar, R. K., Rahu, A. A., Wang, Y., Li, B., Mirjat, M. U., et al. (2023). Integrated effects of water stress and plastic film mulch on yield and water use efficiency of grain maize crop under conventional and alternate furrow irrigation method. *Water* 15:924. doi: 10.3390/w15050924

Zhang, D. Q., Liao, Y. C., and Jia, Z. K. (2005). Research advances and prospects of mulching in arid and semi-arid areas. *Agric. Res. Arid Areas* 23, 208–213.

Zhang, H., Wang, X., You, M., and Liu, C. (1999). Water-yield relations and water use efficiency of winter wheat in the North China Plain. *Irrig. Sci*. 19, 37–45. doi: 10.1007/s002710050069

Zhang, X. Y., Chen, S. Y., Dong, P., Liu, M. Y., and Yong, S. H. (2005). Evapotranspiration, yield and crop coefficient of irrigated maize under straw mulch. *Pedosphere* 15, 576–584.

Zhao, J. B., Mei, X. R., and Zhong, Z. Z. (1996). The effect of straw mulch on crop water use efficiency in dry land. *Scientia Agricultura Sinica* 29, 59–66.

Zou, H., Fan, J., Zhang, F., Xiang, Y., Wu, L., and Yan, S. (2020). Optimization of drip irrigation and fertilization regimes for high grain yield, crop water productivity and economic benefits of spring maize in Northwest China. *Agri. Water Manag.* 230:105986. doi: 10.1016/j.agwat.2019.105986