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Integrated effect of residue management and drip irrigation on crop growth and water productivity of direct seeded rice

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Abstract: Crop residue management and water saving are the two major issues for the sustainability of the rice-wheat cropping system. Therefore, a two-year field experiment was conducted in a split-plot design to study the combined effect of three rice residues (residue incorporation (RI), residue standing (RS) and residue removal (RR) and two wheat residue incorporation (WI) and residue removal (WR) management in main plots and two irrigation regimes, i.e., flood (F) and surface drip (SD) in subplots on the growth and water productivity of direct seeded rice (DSR). During both years, RI-WI resulted in significantly higher plant height (PH), leaf area index (LAI) and dry matter accumulation (DMA) than in other residue management treatments. Drip irrigation significantly increased PH, LAI, DMA grain yield, straw, and biological yield, along with a 9.6% irrigation water savings over flood irrigation. During both years, grain yield, straw and biological yield of DSR were significantly higher in RI-WI than in RR-WR and RR-WI. RI-WI had significantly greater apparent water productivity (AWP) and actual water productivity (RWP) of DSR. Drip irrigation had significantly higher AWP and RWP during both years than flood irrigation except RWP during 2017. Transpiration efficiency (TE) in rice residue incorporation was significantly higher than in rice residue standing and removal. During both years, the TE of drip irrigation was also significantly higher than flood irrigation. So, incorporating rice and wheat residues along with drip irrigation improves crop growth and water productivity.

Keywords: *Oryza sativa* L.; production; groundwater; precipitation; nutrient

Asia accounts for 87% of the global rice farming area while consuming 90% of total rice production (FAO 2018). Based on the Vision 2050 paper produced by the Central Rice Research Institute in 2013 (CRRI 2013), overall rice consumption is expected to reach 121.2 million tons by 2030, 129.6 million tons by 2040, and 137.3 million tons by 2050. Another study estimated that total domestic rice consumption in India will rise by 14 million tons between 2010 and 2035 (Seck et al. 2012). Such an increase in rice production will have to be realised from the major contributing area of India's Indo-Gangetic Plains (IGP), where the water resources are depleting at an alarming rate. Due to excessive groundwater pump-

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ing, water scarcity and increased pumping costs are associated with transplanted rice irrigation (Mahajan et al. 2012). Additionally, free electricity has caused excessive groundwater pumping in the state, causing a long-term decline of 416 mm/year in groundwater levels (Baweja et al. 2017). Due to high production costs, diminishing water resources, and escalating labour availability, traditional transplanted rice is no longer sustainable. Compared with transplanted puddled rice (TPR), direct seeded rice (DSR) provides multiple benefits, including labour savings (40–45%), water savings (30–40%), fuel savings (60–70%), and reduction in greenhouse gas emissions (Mohammad et al. 2018). Introducing short-duration and early-maturity cultivars, adopting integrated weed management techniques, and expanding short-duration cultivars have also influenced farmers to switch from transplanted to DSR crops (Joshi et al. 2013). Without yield compromise, rice establishment by direct seeding requires less water than continuous submersion (Dahiya 2018).

Since the last decade, conservation agricultural (CA) practices have been developed, adopted, and promoted in the Indo-Gangetic Plains of South Asia (Sapkota et al. 2014) to enhance crop yields and profitability and to reduce environmental pollution. Rice residues are generally disposed of by burning, particularly in the regions where combined harvests paddy. According to the assessments, 140 Mt of rice and wheat residue containing about 1.91 Mt of nutrients are produced each year in the Indian subcontinent (Singh and Arya 2021), and about 24.50 and 44.50 Mt of wheat and rice residues are burnt in India (Singh and Sidhu 2014). Paddy straw and wheat straw produced by Punjab are burned in fields nearly 80% of the time (18.4 million tonnes of paddy straw and 8.5 million tonnes of wheat straw) (Kumar et al. 2015). The manual removal or burning of rice residue may cause a huge loss of soil organic matter and available nutrients (Kumar et al. 2019). By reducing carbon emissions and increasing soil organic carbon, judicious management of rice straw alters the soil carbon cycle (Gupta et al. 2022). Incorporating paddy straw before wheat sowing has increased wheat yield compared to removal (Zhao et al. 2019).

As a result of incorporating crop residues, soil quality improved in terms of infiltration rate, hydraulic conductivity, water holding capacity, soil organic carbon, and cation exchange capacity, as well as aggregate stability (Kumar et al. 2018a). Numerous studies have shown that *in-situ* management of paddy straw increases rice-wheat system production and sustainability when compared to conventional techniques (Kumar et al. 2018b, Jat et al. 2019, Saikia et al. 2019, Zhao et al. 2019). Complete rice residue incorporation proved to be the most cost-effective method with the highest returns because of the higher yield against residue burning (Singh and Ranguwal 2022). Crop residue burning has an annual monetary cost of roughly Rs 800–2 000 crore in nutritional loss and Rs 500–1 500 crore in government fertiliser subsidies to Punjab farmers (Alexaki et al. 2019). Direct-seeded rice based on conservation agriculture has been proposed as an alternative to puddled transplanted rice.

Furthermore, combining CA with precision water and N control utilising sub-surface drip (SSD) irrigation in DSR resulted in 23.5% less evaporative loss and 66.0% less deep drainage water loss than puddled transplanted rice (Rana et al. 2022). Surface drip irrigation in DSR resulted in higher grain yield than flood irrigation, with water savings of more than 40% (Sharda et al. 2017). Some experiments in the Indian Punjab exposed that the drip irrigation system can increase on-farm water use efficiency in rice (Kaur 2016). Drip irrigation with 20% cumulative pan evaporation on a 1-day interval outperformed conventional transplanted rice in terms of growth parameters as well as grain and straw production (Singh et al. 2018). Drip irrigation in DSR with a 0.75 IW:CPE ratio is beneficial for higher grain yield and straw yield with a saving of 42.3% of irrigation water compared to a 1.50 IW:CPE ratio (Jagadish et al. 2019). It was therefore hypothesised that dry DSR with residue incorporation under a drip irrigation system could probably decrease the water inputs compared to the conventional method of flood irrigation in rice, along with improved soil health and crop growth. Information is scanty in the literature about detailed water balance characterisation in DSR under drip irrigation. The present study was therefore conducted to evaluate the effects of rice and wheat residue management on crop growth and water productivity of drip-irrigated DSR.

MATERIAL AND METHODS

Field experiments. A two-year field study was carried out at the Punjab Agricultural University's (PAU) research farm, Ludhiana (30°56'N, 75°52'E), India, in the wet season (June–October) of 2016 and 2017. The soil type at the experimental site was coarse

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loamy, calcareous, Typic Psamments (72% sand + 16% clay + 12% silt) with 0.41% organic carbon and a pH of 8.2. The soil's field capacity, permanent wilting point and bulk density were 21.6 (*v*/*v* %), 7.3 (*v*/*v* %) and 1.61 t/m^3, respectively. The steady-state infiltration rate of soil was 7 mm/h. The soil had available N, P and K contents of 58.8, 10.3 and 116.7 mg/kg, respectively. Maximum and minimum temperatures, rainfall, and pan evaporation were measured at the PAU meteorological station, which was about 500 m away from the experimental location (Figure 1). The total rainfall during the crop seasons (June–October) was 491 mm in 2016 and 365 mm in 2017. During the two rice seasons, no difference was observed in monthly mean maximum and minimum temperatures, except that the maximum temperature in June 2016 was higher than in June 2017. The mean monthly maximum temperature during rice season (June–October) ranged from 33.3 °C to 36.9 °C in 2016 and from 33.7 °C to 34.6 °C in 2017, while the monthly mean minimum temperature ranged from 20.3 °C to 28.8 °C in 2016 and from 19.5 °C to 27.5 °C in 2017.

The experiment was laid out in a split-plot design in three replicates with treatment combinations of three rice residues (removal (RR), standing (RS) and incorporation (RI)) and two wheat residues (removal (WR) and residue incorporation (WI) of wheat residue left after making wheat *bhusa*) management practices in main plots and two irrigation regimes (flood (F) and surface drip (D)) in subplots. The main plots (rice residue management) were prepared during wheat season 2015–2016 and 2016–2017 for the following rice season of 2016 and 2017, respectively. The experiment was started during the wheat season; wheat was sown in standing stubbles of transplanted rice (RS) after the incorporation of transplanted rice straw (RI) and after the removal of rice straw (RR). Then, after harvesting wheat with a combine harvester, the wheat residue left over was incorporated after making wheat *bhusa* for animals (WI), and the other was removing wheat straw (WR). Rice residue load in standing (RS) and incorporation (RI) was 6 t/ha. The net plot size of the subplot was 3 × 11 m. Two common irrigations in the form of flood irrigation were applied to all plots to avoid any water deficit and to improve weed control; after that, the irrigation treatments were imposed. Flood irrigation was applied based on 2.25 × pan evaporation (Epan). It means whenever cumulative Epan minus

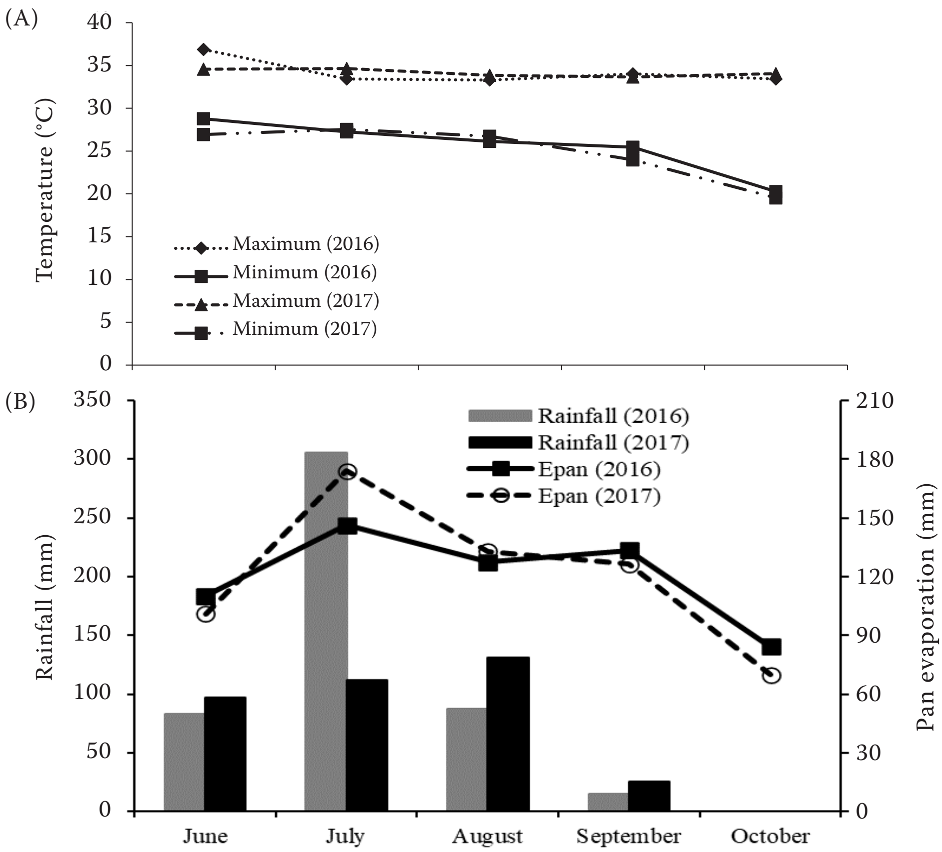

Figure 1. Meteorological data (A) maximum and minimum temperatures and (B) pan evaporation (Epan) and rainfall recorded during the growing seasons in 2016 and 2017

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effective rainfall became 22.2 mm, flood irrigation of 50 mm depth was applied. This way, the flood irrigation interval generally occurred for 4–6 days, depending on weather conditions. Drip irrigation was applied based on 2.25 × crop evapotranspiration (ETc) when tensiometers installed at 15 cm soil depth reached a soil matric potential (SMP) of 10 kPa. This way, the drip irrigation interval generally occurred at 1–3 days, depending on weather conditions. A surface drip irrigation system was introduced within ten days of sowing and figured out to guarantee uniform application. The quantity of irrigation was measured by a water meter installed on the main line. The drip framework comprised of polyethene laterals of 8 mm radius were laid parallel to crop lanes, and each lateral served two crop lanes. The laterals were furnished with in-line emitters having a capacity of 2.2 L/h. The lateral spacing of 40.0 cm was taken with in-line drippers at 30.0 cm apart, so the 100% area was wetted.

Rice residue removal plots were prepared by cultivating twice using a disc harrow and planking with a wooden board. In RS plots, wheat seeds were sown into standing stubbles of rice. In RI plots, rice residues were incorporated into the soil with a rotavator. Rice (a medium-duration cultivar, PR 121) seeds were sown by DSR drill at a seed rate of 25 kg/ha at 20 cm row spacing on June 15 during both years (2016 and 2017). The field was irrigated the next day after sowing. A full dose of P (5.5 kg P/ha from diammonium phosphate) and full K (20.7 kg K/ha from murite of potash) was applied during land preparation as a basal dose. The N (150 kg N/ha from urea) was applied in 4 equal splits, first at basal dose, second at 4th, third at 7th and fourth at 10th week after sowing. The crop was harvested in the third week of October during both years. Weeds were managed using a pre-emergence herbicide (pendimethalin 0.375 mg/kg soil) applied two days after sowing (DAS) and a post-emergence herbicide (bispyribac-sodium) applied 20 days after sowing. Weeds that escaped these treatments were manually eradicated at 42 DAS. At 20 and 40 DAS, all plots were sprayed twice with 1% ferrous sulfate solution.

Measurements. The soil water balance components for the soil profile/root zone of 100 cm were calculated as follows:

$$I + P = ETa + D + R + \Delta S \quad (1)$$

where: I – irrigation (mm); P – precipitation (mm); ETa – crop evapotranspiration (mm); D – soil water drainage (mm); R – runoff (mm); ΔS – change in soil moisture storage of the cropping season (mm). I and P were directly measured, ETa was recorded from the lysimeters of 100 cm length, D was calculated as the surplus water than field capacity storage that left the 100 cm of the soil profile, ΔS was calculated as the difference in soil moisture storage at sowing time and the harvest time. Runoff was zero as bunds of 300 mm in height were created, and limited irrigation was applied. The rain gauge at the study site measured the rainfall received during the cropping season. Profile soil moisture (0–100 cm) was measured with a soil moisture sensor (frequency domain reflectometry) before and after each irrigation. Initial profile moisture and moisture at harvesting were also measured gravimetrically. Daily ETa was measured from lysimeters having sealed bottoms embedded in the field with the same number of treatments. Lysimeters were constructed with polyvinyl chloride pipes (PVC) of 22.9 cm diameter and 100 cm height. Every lysimeter was filled up to 90 cm depth. Daily volumetric soil moisture was measured for 0–90 cm soil depth at cm depth interval TDR having two metallic probes. Two parallel holes were created at each 10 cm depth in all lysimeters to insert moisture meter probes into the lysimeter. Change in soil moisture every 24 h was recorded to calculate ETa (mm per day). According to Brar et al. (2012), real water productivity (kg/m^3) was determined as the ratio of grain yield to evapotranspiration:

$$RWP = GY/ETa \times 10 \quad (2)$$

where: RWP – real water productivity (kg/m^3); ETa – crop evapotranspiration (mm); GY – grain yield (t/ha).

$$AWP = \frac{GY}{I} \quad (3)$$

where: AWP – apparent water productivity (kg/m^3); I – irrigation water applied (m^3).

Plant height was recorded from the ground surface to the top of the highest leaf on the main shoot with the help of a meter rod at 30, 60 and 90 DAS and harvesting. The average height of ten plants was obtained and presented as the mean plant height (cm). To collect data on dry matter accumulation (DMA), plants from half meter row length from each plot were harvested, sun-dried and then dried in an oven at 60 °C temperature till constant weight was achieved at 30, 60 and 90 DAS and harvesting. DMA was expressed t/ha. The leaf area index (LAI) of each experimental plot was recorded by SSI SunScan canopy analyser of Delta T devices (Cambridge, UK) at 45, 60, 75, 90 and 105 DAS. All treatments harvested the crop at 15% to 18% grain moisture content. Grain yield was expressed in t/ha and adjusted to 14% grain moisture content. Bundle weight before threshing was recorded after complete sun drying,

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and straw yield was obtained after subtracting grain weight from whole bundle weight and was expressed in t/ha. Harvest index (HI) values were calculated as follows:

$$HI = (\text{grain yield/biological (grain + straw) yield}) \times 100.$$

Harvest index values were expressed in per cent.

Statistical analysis. The analysis of variance (ANOVA) approach was used (SPSS 16.0 software, Chicago, USA) to find significant differences between the effects of the different treatments at $P < 0.05$. Data recorded on various investigation parameters were analysed statistically using a statistical package of CPCS-I (Cheema and Singh 1991). The comparison of different treatments was discussed at a 5% significance level. The year was the most important element in boosting precision in pooled analysis. Furthermore, the regression process was utilised to investigate the nature of the association between various factors.

RESULTS AND DISCUSSION

Plant height. The data about the effect of rice and wheat residue management and irrigation on periodic plant height (cm) of direct seeded rice are presented in Table 1. Plant height of DSR was significantly affected due to residue management at 30, 60, and 90 DAS and harvest during both years. RI-WI resulted in significantly higher plant height during both years than other residue management treatments at 30, 60, and 90 DAS and harvest. However, in RR-WR, plant height was significantly lower than all other residue management treatments on all days after sowing. RI plant height was statistically at par with RS and RS-WI when measured at 30, 60 and 90 DAS. The increase in plant height with residue incorporation is ascribed to more availability of nutrients to crops through residue decomposition (Bastola et al. 2021).

Plant height in RR-WR was also statistically on par with RR-WI when measured at 30, 60, and 90 DAS and harvest. During both years, plant height was significantly higher in drip irrigation than flood irrigation at all DAS and harvesting. The increase in plant height of DSR with drip irrigation may be due to the continuous availability of water and nutrients (Singh et al. 2018).

Leaf area index. Leaf area index (LAI) is a dimensionless plant character that modifies plant canopy. The data on LAI of DSR was recorded at 45, 60, 75, 90 and 105 DAS (Table 2). LAI increased successively with advancement in crop age. The maximum value attained was approximately 90 DAS, and after that, LAI decreased due to the senescence of leaves during both years, irrespective of treatment. Significant effects of residue management and irrigation regimes were observed during both years. However, interaction effects were not significant. Among residue management treatments, RI-WI resulted in significantly higher LAI as compared to all other

Table 1. Effect of residue management and irrigation on periodic plant height (cm) of direct seeded rice

Treatment	2016				2017			
	days after sowing			at harvesting	days after sowing			at harvesting
	30	60	90		30	60	90	
Straw management								
RI	26.15^{ab}	64.61^{ab}	91.57^{ab}	104.95^{ab}	25.51^{a}	63.56^{a}	90.81^{ab}	101.12^{a}
RI-WI	27.90^{b}	66.72^{b}	93.44^{b}	106.54^{b}	27.03^{b}	65.51^{b}	93.32^{b}	103.56^{b}
RS-WR	23.56^{ac}	62.03^{ac}	89.06^{ac}	102.06^{c}	22.55^{c}	59.76^{cd}	85.80^{cd}	97.60^{cd}
RS-WI	24.94^{ad}	63.25^{ac}	90.19^{ad}	103.24^{ad}	23.86^{ac}	62.18^{a}	88.51^{ac}	99.43^{c}
RR-WR	21.54^{c}	59.83^{c}	86.93^{c}	100.14^{c}	20.4^{d}	57.55^{d}	83.52^{d}	94.98^{d}
RR-WI	22.83^{cd}	61.02^{ac}	88.24^{cd}	101.59^{cd}	21.60^{c}	58.97^{d}	84.72^{d}	96.53^{d}
Irrigation regimes								
Flood	22.45^{a}	60.81^{a}	87.88^{a}	100.9^{a}	21.39^{a}	58.72^{a}	84.72^{a}	96.35^{a}
Drip	26.52^{b}	65.00^{b}	91.93^{b}	106.5^{b}	25.59^{b}	63.79^{b}	90.84^{b}	101.39^{b}
Interactions	ns	ns	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

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Table 2. Effect of residue management and irrigation regimes on periodic leaf area index of direct seeded rice

Treatment	2016					2017				
	days after sowing					days after sowing				
	45	60	75	90	105	45	60	75	90	105
Straw management										
RI	1.43^{ab}	2.46^{ab}	3.30^{ab}	3.84^{ab}	3.73^{ab}	1.51^{ab}	2.55^{ab}	3.38^{ab}	3.86^{ab}	3.73^{a}
RI-WI	1.54^{b}	2.61^{b}	3.47^{b}	4.00^{b}	3.90^{b}	1.63^{b}	2.70^{b}	3.58^{b}	4.07^{b}	3.94^{b}
RS-WR	1.31^{ac}	2.31^{ac}	3.07^{ac}	3.55^{ac}	3.42^{a}	1.36^{ac}	2.36^{ac}	3.08^{c}	3.56^{c}	3.42^{c}
RS-WI	1.37^{a}	2.41^{a}	3.22^{abc}	3.70^{ad}	3.56^{ab}	1.39^{ac}	2.45^{a}	3.28^{ac}	3.76^{a}	3.62^{a}
RR-WR	1.19^{c}	2.15^{c}	2.91^{c}	3.38^{c}	3.26^{c}	1.27^{c}	2.18^{c}	2.97^{c}	3.34^{c}	3.26^{c}
RR-WI	1.27^{c}	2.23^{c}	2.98^{ac}	3.44^{cd}	3.30^{c}	1.32^{c}	2.26^{c}	3.03^{ac}	3.45^{c}	3.34^{c}
Irrigation regimes										
Flood	1.25^{a}	2.22^{a}	2.99^{a}	3.45^{a}	3.35^{a}	1.29^{a}	2.26^{a}	3.02^{a}	3.43^{a}	3.33^{a}
Drip	1.45^{b}	2.50^{b}	3.33^{b}	3.86^{b}	3.70^{b}	1.53^{b}	2.57^{b}	3.42^{b}	3.92^{b}	3.77^{b}
Interactions	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

residue management treatments during both years at all DAS. Earlier studies also observed increased LAI of rice with residue incorporation (Bastola et al. 2021). However, in RR-WR, LAI was significantly lower than all other residue management treatments on all days after sowing during both years. In RI, LAI was statistically at par with RS and RS-WI when measured at 45, 60, 75, 90 and 105 DAS during 2016 and at 45 and 60 DAS in 2017. The leaf area index in RR-WR was also statistically at par with RR-WI when measured at all DAS during both years. LAI was significantly higher in drip irrigation during both years compared to flood irrigation at all DAS and harvesting. The superiority of drip over flood--irrigated rice regarding leaf area index has already been observed (Prashant et al. 2019).

The accumulation of dry matter is another way to express the growth activity of a plant. The data on the residue management and irrigation on periodic dry matter accumulation (DMA) of DSR are presented in Table 3. The data presented in Table 3 revealed that dry matter accumulation was significantly affected due to various residue management and irrigation regimes at 60 and 90 DAS and harvest during both years. Among residue management treatments, RI-WI resulted in significantly higher DMA as compared to all other residue management treatments during both years at all DAS. However, in RR-WR, DMA was significantly lower than all other residue management treatments on all days after sowing during both years. DMA was statistically at par with RI-WI and RS-WI in RI when measured at 60, and 90 DAS and harvesting during both years. Dry matter accumulation in RR-WR was also statistically at par with RR-WI and RS-WR when measured at all DAS during both years. During both years, DMA was significantly higher in drip irrigation than flood irrigation at all DAS and harvesting. Higher DMA with drip irrigation over flood has also been observed (Prashant et al. 2019).

Grain yield. The effect of residue management and irrigation on grain yield (at 14% moisture) of DSR is given in Table 4. The grain yield of DSR was significantly higher in RI-WI than in RR-WR and RR-WI during both years. An increase in grain yield of DSR with crop residue incorporation or retention has also been reported in earlier studies (Mahmood and Ali 2015, Bastola et al. 2021). However, no significant difference in grain yield was observed in RI, RI-WI, RS-WR, and RS-WI during 2016. Grain yield in RI and RI-WI was also at par during both years. During both years, drip irrigation significantly increased grain yield compared to flood irrigation. Earlier studies also reported that drip irrigation produced significantly more grain yield than the flood irrigation method (Sharda et al. 2017, Bansal et al. 2018, Singh et al. 2018, Jagadish et al. 2019).

The effect of residue management and irrigation on soil organic carbon (SOC) of surface soil after 2 years of DSR is presented in Figure 2A. The SOC was significantly higher in RI-WI compared to all other residue management treatments. Soil organic

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Table 3. Effect of residue management and irrigation regimes on periodic dry matter accumulation (t/ha) of direct seeded rice

Treatment	2016			2017		
	days after sowing		at harvesting	days after sowing		at harvesting
	30	60		30	60	
Straw management						
RI	2.76^{ab}	5.70^{ab}	10.96^{ab}	2.84^{ac}	6.36^{ab}	11.45^{ab}
RI-WI	3.17^{a}	6.32^{a}	11.77^{a}	3.33^{a}	6.71^{a}	12.40^{a}
RS-WR	2.00^{c}	5.11^{bc}	9.89^{bc}	2.27^{b}	5.67^{bc}	10.24^{b}
RS-WI	2.56^{b}	5.37^{b}	10.63^{b}	2.61^{c}	6.19^{b}	10.98^{b}
RR-WR	1.47^{c}	4.42^{c}	8.77^{c}	1.58^{d}	4.94^{c}	8.46^{c}
RR-WI	1.88^{c}	4.80^{c}	9.47^{c}	1.94^{bd}	5.40^{bc}	9.81^{bc}
Irrigation regimes						
Flood	1.86^{a}	4.79^{a}	9.49^{a}	1.95^{a}	5.39^{a}	9.75^{a}
Drip	2.75^{b}	5.78^{b}	11.00^{b}	2.90^{b}	6.34^{b}	11.36^{b}
Interactions	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

carbon was at par in RI and RS-WI but significantly higher than RS-WR, RR-WR and RR-WI. Both rice and wheat residue incorporation in combination (RI-WI) increased the SOC by 8.97, 19.72, 11.84, 28.78 and 23.18% over RI, RS-WR, RS-WI, RR-WR and RR-WI, respectively. There was no significant difference in drip and flood irrigation treatments on SOC. Exotic straw application enhances SOC input, resulting in an increase in SOC concentrations as long as the soil is not totally saturated with C (Gupta et al. 2022). The increased SOC due to residue integration could be attributed to increased soil moisture and nutrient availability for microbial development after straw addition (Wang et al. 2015). Grain yield was significantly and linearly correlated to SOC with a 0.94 coefficient of determination (Figure 2B).

Table 4. Effect of residue management and irrigation on grain yield (t/ha), straw yield (t/ha), biological yield (t/ha) and harvest index (HI, %) of direct seeded rice

Treatment	2016				2017			
	grain yield	straw yield	biological yield	HI	grain yield	straw yield	biological yield	HI
Straw management								
RI	5.78^{ab}	7.68^{ab}	13.46^{ab}	43.07^{ab}	6.07^{ab}	7.94^{ab}	14.00^{ab}	43.62^{a}
RI-WI	6.11^{b}	7.96^{a}	14.07^{a}	43.64^{a}	6.38^{a}	8.36^{a}	14.74^{a}	43.29^{a}
RS-WR	5.31^{bc}	7.23^{ab}	12.54^{bc}	42.25^{ab}	5.48^{bc}	7.37^{bc}	12.85^{bc}	42.47^{a}
RS-WI	5.55^{abc}	7.51^{ab}	13.07^{abc}	42.36^{ab}	5.69^{ab}	7.74^{ab}	13.43^{bc}	42.45^{a}
RR-WR	4.87^{c}	6.81^{b}	11.68^{c}	41.51^{b}	4.92^{c}	6.77^{c}	11.70^{c}	42.13^{a}
RR-WI	5.17^{c}	7.11^{b}	12.29^{c}	42.03^{ab}	5.41^{bc}	7.32^{bc}	12.74^{c}	42.48^{a}
Irrigation regimes								
Flood	5.08^{a}	7.04^{a}	12.12^{a}	41.79^{a}	5.29^{a}	7.27^{a}	12.56^{a}	42.19^{a}
Drip	5.85^{b}	7.73^{b}	13.58^{b}	43.16^{a}	6.03^{b}	7.90^{b}	13.92^{b}	43.29^{a}
Interactions	ns	ns	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

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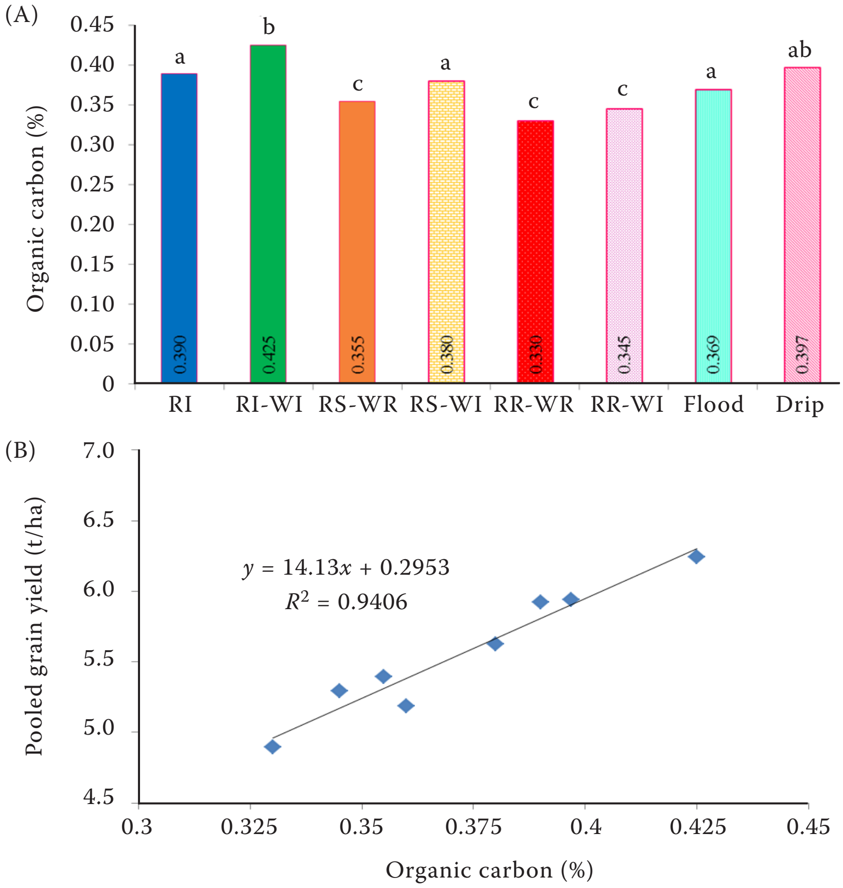

Figure 2. (A) Soil organic carbon under different residue management options and irrigation regimes, and (B) the relationship between pooled grain yield and soil organic carbon. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal

Straw and biological yield. The effect of rice and wheat residue management and irrigation on straw and biological yield of DSR is presented in Table 4. The straw and biological yield of DSR was significantly higher in RI-WI than in RR-WR and RR-WI during both years. These results agree with earlier studies (Mahmood and Ali 2015, Bastola et al. 2021). However, no significant difference was observed in RI and RI-WI during both years. Straw and biological yield were at par in RI, RS-WR, and RS-WI during both years. Straw and biological yield in RR-WR and RR-WI was also at par during both years. During both years, drip irrigation significantly increased straw yield compared to flood irrigation. Earlier studies also reported increased straw with drip compared to flood irrigation (Bansal et al. 2018, Singh et al. 2018, Jagadish et al. 2019, Prashant et al. 2019).

Harvest index. The effect of residue management and irrigation on the harvest index of DSR is presented in Table 4. Data analysis showed that the HI of DSR was significantly higher in RI-WI than in RR-WR and RR-WI treatments during 2016 only. So, rice and wheat residue incorporation resulted in a higher harvest index than residue removal. The highest harvest index of DSR with straw incorporation has also been reported earlier (Pragya et al. 2018). However, during 2017, HI was at par in all residue management treatments. During both years, no effect of irrigation was observed on HI.

Field water balance. Calculating field water balance components is critical for proper irrigation management and water loss prevention. Table 5 shows the water balance components of DSR for both years separately. Rainfall amounts of 490.9 and 365.4 mm were received in 2016 and 2017, respectively. The data presented in Table 5 showed that during crop season 2016, 1 095 and 995 mm irrigation was applied in flood and drip irrigated plots, respectively, indicating significant (9.1%) irrigation water saving with drip irrigation over the flood. The RI, RI-WI, RS-WR, RS-WI, RR-WR, and RR-WI treatments received 104.3, 103.8, 104.4, 1 048, 1 053 and 1 045 mm of irrigation water, which indicated not much difference in irrigation. During 2017, an irrigation amount of 1 170 and 1 058 mm was applied in flood and drip irrigated plots, respectively, indicating significant (9.6%) irrigation water saving with drip irrigation over the flood. No significant difference in irrigation

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Table 5. Effect of residue management and irrigation on water balance components (mm) of direct seeded rice

Treatment	2016					2017				
	rain	IR	ETa	D	ΔS	rain	IR	ETa	D	ΔS
Straw management										
RI	491	1 043[a]	603[a]	806[a]	125[a]	365	1 112[a]	668[a]	683[a]	126[a]
RI-WI	491	1 038[a]	631[b]	772[b]	126[a]	365	1 103[a]	678[a]	664[a]	127[a]
RS-WR	491	1 044[a]	590[ac]	824[a]	121[a]	365	1 115[a]	646[b]	712[b]	122[a]
RS-WI	491	1 048[a]	604[a]	812[a]	123[a]	365	1 105[a]	650[ab]	696[ab]	125[a]
RR-WR	491	1 053[a]	576[c]	856[c]	112[a]	365	1 127[a]	622[c]	758[c]	113[a]
RR-WI	491	1 045[a]	592[ac]	828[a]	116[a]	365	1 121[a]	643[b]	727[b]	117[a]
Irrigation regimes										
Flood	491	1 095[a]	592[a]	876[a]	119[a]	365	1 170[a]	616[a]	799[a]	120[a]
Drip	491	995.1[b]	60.8[b]	757[b]	122[a]	365	1 058[b]	684[b]	616[b]	123[a]
Interactions	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. IR – irrigation; ETa – crop evapotranspiration; D – soil water drainage; ΔS – change in soil moisture storage of the cropping season; RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

application was observed in RI, RI-WI, RS-WR, RS-WI, RR-WR and RR-WI treatments. Similar results of irrigation water saving in DSR with drip irrigation have been reported (Sharda et al. 2017, Bansal et al. 2018, Jagadish et al. 2019). During both years, no significant difference in profile moisture storage among crop residue management and irrigation regimes was observed. During 2016, seasonal soil moisture drainage was significantly low in RI-WI and significantly higher in RR-WR compared to other residue management treatments.

Soil moisture drainage was on a par in RI, RS, RS-WI and WI residue management treatments. During 2017, seasonal soil moisture drainage was significantly higher in RR-WR than in other residue treatments. Soil moisture drainage was significantly lower in both RI

Table 6. Effect of residue management and irrigation on apparent water productivity (AWP), real water productivity (WP_{ET}) and transpiration efficiency (TE) of direct seeded rice

Treatment	2016			2017		
	AWP	WP_{ET}	TE	AWP	WP_{ET}	TE
	(kg/m³)					
Straw management						
RI	0.55[ab]	0.96[a]	1.82[a]	0.55[a]	0.91[ab]	1.65[ab]
RI-WI	0.59[a]	0.97[a]	1.81[a]	0.58[a]	0.94[a]	1.67[a]
RS-WR	0.51[b]	0.90[ab]	1.75[b]	0.49[b]	0.85[bc]	1.62[b]
RS-WI	0.53[ab]	0.92[ab]	1.75[b]	0.51[ab]	0.88[b]	1.62[b]
RR-WR	0.46[b]	0.85[b]	1.71[c]	0.44[b]	0.79[c]	1.55[c]
RR-WI	0.49[b]	0.87[ab]	1.71[c]	0.48[b]	0.84[bc]	1.60[b]
Irrigation regimes						
Flood	0.46[a]	0.86[a]	1.73[a]	0.45[a]	0.86[a]	1.56[a]
Drip	0.59[b]	0.96[b]	1.79[b]	0.57[b]	0.88[a]	1.61[b]
Interactions	ns	ns	ns	ns	ns	ns

Treatments with different lowercase letters are significantly different at $P < 0.05$. RI – residue incorporation; WI – wheat residue incorporation; RS – residue standing; WR – residue removal; RR – residue removal; ns – not significant

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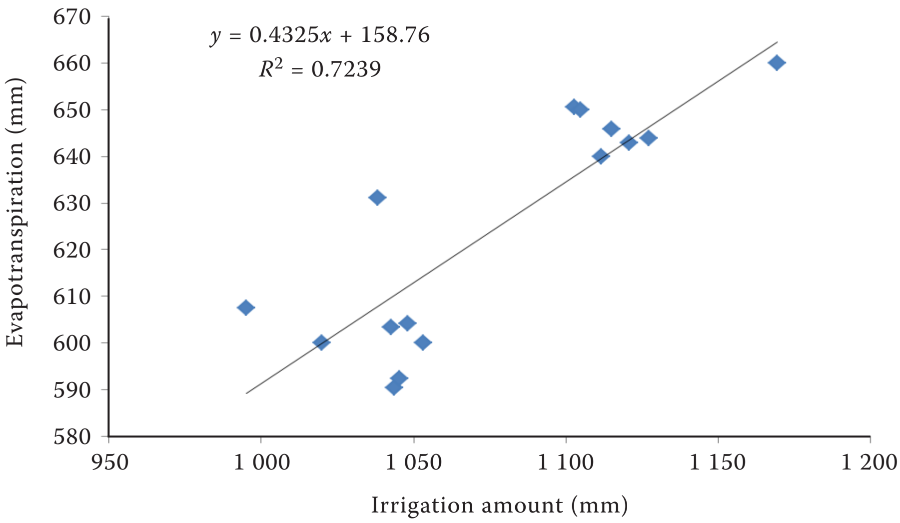

Figure 3. Relation between crop evapotranspiration and irrigation water applied for the pooled data

and RI-WI compared to other residue management treatments, but it was at par in RI, RI-WI and RS-WI. In RS, RS-WI and WI, soil moisture drainage was at par. However, seasonal soil moisture drainage was significantly higher by 15.7 and 29.7 per cent in flood irrigation compared to drip irrigation during 2016 and 2017, respectively. During both years, significantly higher evapotranspiration (ETa) was recorded in RI-WI (631 and 678 mm) and lowest in RR-WR (576 and 622 mm). Residue incorporation resulted in the highest ETc and received the lowest irrigation amount, which shows the best utilisation of applied water these results follow earlier studies (Mohammad et al. 2018).

A linear relationship was found between irrigation water applied and ETa (Figure 3) with R^2 values of 0.72 for pooled data. The assimilation of residue reduces the unproductive component of evapotranspiration. It promotes the conversion of water transpired into the dry matter by producing a favourable root environment and increasing the soil's water-holding capacity (Liu et al. 2017). High ETa in residue incorporation treatment may be due to a better supply of soil moisture because the incorporation of crop residues increases the transpiration part of ETa by creating a barrier to the capillary movement of soil moisture. A linear relationship was also observed between DSR grain yield and ETa (Figure 4), with two-year pooled R2 values of 0.58. The highest grain yield was observed in the treatment under which the highest amount of ETa was recorded.

Apparent and real water productivity. RI-WI had significantly higher apparent water productivity (AWP) and real water productivity (RWP) of DSR

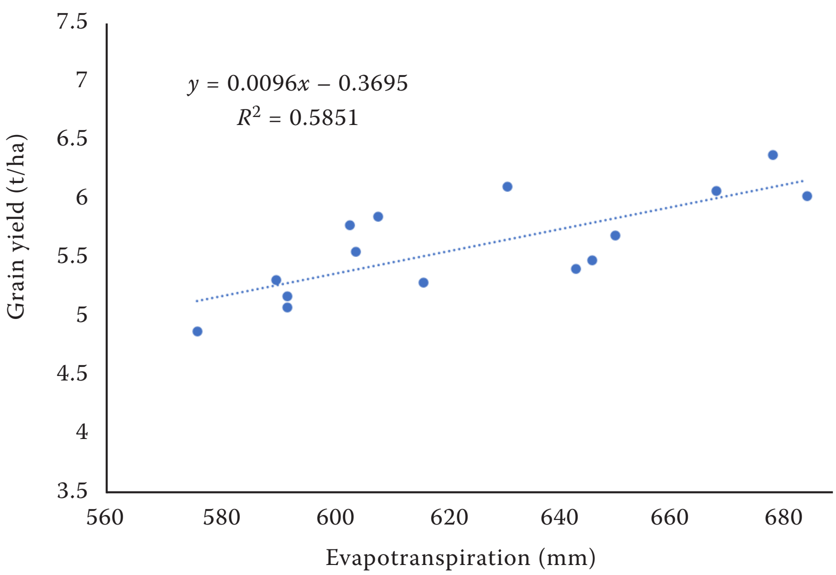

Figure 4. Direct seeded rice grain yield response to crop evapotranspiration

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(Table 6) than RR-WR in 2016. However, in 2017, AWP and RWP in IR-WI were significantly higher than in RR-WR and RR-WI treatments. However, both years, AWP and RWP of RI, RS-WR, and RS-WI were at par. A significant increase in water productivity of DSR with residue incorporation has also been observed in earlier studies (Mohammad et al. 2017). Drip irrigation had significantly higher AWP during both years than flood irrigation, but the RWP of drip was significantly higher than flood only during 2016. Earlier studies also supported that drip-irrigated DSR has higher water productivity than flood irrigation (Sharda et al. 2017, Singh et al. 2018, Jagadish et al. 2019, Prashant et al. 2019).

Transpiration efficiency. During 2016, the transpiration efficiency (TE) of DSR in rice residue incorporation (RI and RI-WI) was significantly higher than rice residue standing (RS-WR, RS-WI) and rice residue removal (RR-WR and RR-WI). Rice residue standing (RS-WR and RS-WI) also has significantly higher TE than removal (RR-WR and RR-WI). Greater crop transpiration is the major advantage of residue incorporation in semi-arid climates (Liu et al. 2017) due to increased soil water retention. During 2017, RI-WI had significantly higher TE than all other residue management treatments. Residue incorporation also reduces soil evaporation, which further increases the water use efficiency of crops (Liu et al. 2017). During both years, the TE of drip irrigation was significantly higher than flood irrigation.

Finally, incorporating rice residue alone and in combination with wheat residue was superior in enhancing soil organic carbon, significantly increasing PH, LAI, DMA, grain yield, straw and biological yield of DSR, and an increase in evapotranspiration and decreased unproductive water loss through drainage. Rice and wheat residue incorporation increased the soil organic carbon, which further increased the grain yield of DSR, as indicated by a linear correlation between grain yield and SOC. Significantly higher AWP, RWP and TE were observed in rice residue incorporation than in rice residue standing and removal. Drip irrigation saved a significant amount of irrigation water, which resulted in higher AWP, RWP and TE of DSR. Rice and wheat residue incorporation and drip irrigation are viable options for improving soil organic carbon, crop growth and grain yield and saving irrigation water.

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