Agricultural Water Management 283 (2023) 108308

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Appraisal of complementarity of subsurface drip fertigation and conservation agriculture for physiological performance and water economy of maize

Kiranmoy Patra [a], C.M. Parihar [a,*], H.S. Nayak [a], Biswajit Rana [a], D.R. Sena [a,b], Anjali Anand [a], K. Srikanth Reddy [a], Manojit Chowdhury [a], Renu Pandey [a], Atul Kumar [a], L.K. Singh [c], M.K. Ghatala [d], H.S. Sidhu [c,e], M.L. Jat [f,g,**]

[a] ICAR-Indian Agricultural Research Institute (IARI), New Delhi, India
[b] International Water Management Institute, New Delhi, India
[c] Borlaug Institute for South Asia (BISA)-CIMMYT, Ludhiana, India
[d] International Maize and Wheat Improvement Center (CIMMYT), South Asia Regional Office, Bangladesh
[e] Punjab Agricultural University (PAU), Ludhiana, Punjab, India
[f] International Maize and Wheat Improvement Center (CIMMYT), South Asia Regional Office, Kathmandu, Nepal
[g] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad, India

A R T I C L E I N F O

Handling Editor - J.E. Fernández

Keywords:
Conservation agriculture
Net returns
Nitrogen use efficiency
Photosynthesis
Subsurface drip irrigation & fertigation
Water productivity

A B S T R A C T

The Indo-Gangetic Plains (IGP) in north-west (NW) India are facing a severe decline in ground water due to prevalent rice-based cropping systems. To combat this issue, conservation agriculture (CA) with an alternative crop/s, such as maize, is being promoted. Recently, surface drip fertigation has also been evaluated as a viable option to address low-nutrient use efficiency and water scarcity problems for cereals. While the individual benefits of CA and sub-surface drip (SSD) irrigation on water economy are well-established, information regarding their combined effect in cereal-based systems is lacking. Therefore, we conducted a two-year field experiment in maize, under an ongoing CA-based maize-wheat system, to evaluate the complementarity of CA with SSD irrigation through two technological interventions— CA+ (residue retained CA + SSD), PCA+ (partial CA without residue + SSD) – at different N rates (0, 120 and 150 kg N ha^{-1}) in comparison to traditional furrow irrigated (FI) CA and conventional tillage (CT) at 120 kg N ha^{-1}. Our results showed that CA+ had the highest grain yield (8.2 t ha^{-1}), followed by PCA+ (8.1 t ha^{-1}). The grain yield under CA+ at 150 kg N ha^{-1} was 27% and 30% higher than CA and CT, respectively. Even at the same N level (120 kg N ha^{-1}), CA+ outperformed CA and CT by 16% and 18%, respectively. The physiological performance of maize also revealed that CA+ based plots with 120 kg N ha^{-1} had 12% and 3% higher photosynthesis rate at knee-high and silking, respectively compared to FI-CA and CT. Overall, compared to the FI-CA and CT, SSD-based CA+ and PCA+ saved 54% irrigation water and increased water productivity (WP) by more than twice. Similarly, a greater number of split N application through fertigation in PCA+ and CA+ increased agronomic nitrogen use efficiency (NUE) and recover efficiency by 8–19% and 14–25%, respectively. Net returns from PCA+ and CA+ at 150 kg N ha^{-1} were significantly higher by US$ 491 and 456, respectively than the FI-CA and CT treatments. Therefore, CA coupled with SSD provided tangible benefits in terms of yield, irrigation water saving, WP, NUE and profitability. Efforts should be directed towards increasing farmers' awareness of the benefits of such promising technology for the cultivating food grains and commercial crops such as maize. Concurrently, government support and strict policies are required to enhance the system adaptability.

* Correspondence to: ICAR-Indian Agricultural Research Institute (IARI), New Delhi-110012, India.
** Correspondence to: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad-502324, India.
E-mail addresses: pariharcm@gmail.com (C.M. Parihar), m.jat@cgiar.org (M.L. Jat).

https://doi.org/10.1016/j.agwat.2023.108308
Received 14 September 2022; Received in revised form 1 April 2023; Accepted 6 April 2023
Available online 25 April 2023
0378-3774/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction

The traditional rice-wheat (RW) systems in India's Indo-Gangetic Plains (IGP) are being criticised for its environmental and sustainability issues, which includes declining factor productivity, soil health deterioration, residue burning and greenhouse gas emissions, and deepening of groundwater levels (Jat et al., 2019; Bhatt et al., 2021). The decline in the groundwater table has led the governments of Punjab and Haryana to declare certain areas as "dark zones" where rice cultivation is no longer considered sustainable. The groundwater table in north western (NW) India declined 0.2 m yr^{-1} during 1973–2001, while during 2000–2006 it got hastened by fivefold (1.0 m yr^{-1}) (Humphreys et al., 2010). The deepening of ground-water table demands installation of heavy-power pump for lifting groundwater, which increases the input energy use and cost of cultivation. Further, if appropriate measures on prudent groundwater use are not implemented promptly, the IGP in NW India may face a severe water shortage, which could lead to widespread socioeconomic stress. Alternative techniques to save water and increase irrigation water productivity comprise, shifting to conservation agriculture (CA) practices (no tillage and straw mulching), cultivation on permanent raised beds (PB), soil matric potential based irrigation scheduling, micro-irrigation methods and diversification of rice with C_4 crop like maize (Yadvinder-Singh et al., 2014; Majeed et al., 2015; Parihar et al., 2016a; Patra et al., 2021a).

There are numerous benefits associated with replacement of rice with maize in the existing RW cropping system towards improvement of soil health (Jat et al., 2013), biomass accumulation, radiation use efficiency (Patra et al., 2021a), system productivity (Devkota et al., 2013; Parihar et al., 2016b; Choudhary et al., 2018). Diversification of RW with maize-wheat (MW) system is a win-win solution for achieving sustainable water use, as the water productivity (WP) of maize is 8–22 times higher than rice (Gathala et al., 2013) and maize requires 80–85% less water to produce one kg of grain than rice (Bouman, 2009). For such reasons, the area under maize cultivation in North-west (NW) India has recently increased, owing largely to favourable government policies that encourage maize cultivation to save irrigation water and electricity costs (Sharma et al., 2015). However, conventional-till maize (CT) cultivation comprising of 6–7 tillage operations and flood irrigation, results in high energy use, unproductive loss of irrigation water and nitrogen (N) fertilizer (Sandhu et al., 2019; Mutuku et al., 2020; Patra et al., 2021b) and overall economic non-profitability (Aryal et al., 2015).

In the recent time, with emergence of water scarcity issue, drip irrigation gained attention as an economically viable option for irrigating the field crops such as maize (Yolcu and Cetin, 2015; Jat et al., 2019; Patra et al., 2021a), and wheat (Chen et al., 2015; Chouhan et al., 2015; Sidhu et al., 2019) to increase the WP. However, because of field inconvenience, like interference of drip laterals with tillage and harvesting implements and intercultural operations, the field adoption of surface drip irrigation was very less. Sub-surface drip overcomes these bottlenecks and improve farmers' acceptance of drip irrigation in cereal-based systems. In contrast to surface drip irrigation, the SSD system reduces evaporation losses from the soil surface, allows water and nutrients to be delivered directly to the crop root zone, resulting in efficient water and nutrient use, reduction in weed emergence, labour costs, and facilitates seeding with CA-based no-tillage practices (Jat et al., 2019; Sidhu et al., 2019). Furthermore, precise N fertigation in multiple splits through SSD may open a new avenue for redesigning N management protocol in CA based maize system. With conventional broadcasting of N fertilizers in CA, a larger amounts of N fertilizers remain on crop residues, which encourages volatilization losses (Wan et al., 2021). Thus, to increase the NUE and water economy, effective N placement along with water at the active crop root zone via SSD in residue-retained CA-based maize systems could be beneficials.

While numerous studies have examined the individual benefits of CA and SSD in terms of water and nitrogen savings, there is a lack of comprehensive research exploring complementarity of CA and SSD can work together to impact crop physiological responses, crop productivity, water productivity (WP), and nitrogen use efficiency (NUE) in cereals such as maize. In light of existing knowledge gaps, a 2-year study was conducted with the objectives of i) assessing the effect of bundling of CA with SSD (CA+) at different N doses on physiological performance of maize, and ii) estimating the yield benefits, irrigation water savings, water and N use efficiency and farm profitability of maize under MW system in different combinations of tillage, nitrogen, irrigation and residue management. It was hypothesized that coupling of CA with SSD would improve crop physiological responses, and thus water and N use efficiency over furrow irrigated CA and CT-plots.

2. Materials and methods

2.1. Experimental site and climate

A two-year field experiment (2018 and 2019) was conducted under an ongoing CA-based maize-wheat (MW) system, initiated since 5-years (in *kharif* 2014) at the fixed-site with same set of technological interventions at the Borlaug Institute for South Asia (BISA)-CIMMYT (30.99°N, 75.44°E, 229 m above the sea level), Punjab, India. The climate is semi-arid and sub-tropical with three well-defined seasons, i.e., hot and dry summer season (March-June), wet monsoon season (late June-mid September), dry winter season (October-February). The experimental site has an alluvial origin, flat and well-drained sandy loam soil (Typic Haplustept), which was fairly uniform to a depth of 120 cm. The pH (1:2 soil water ratio) and EC are 7.9–8.5 and 0.58 dS m^{-1}, respectively.

2.2. Climatic data during experimentation

The annual average rainfall is 734 mm, with approximately 75–80% falling between July and October. The rainfall, maximum temperature (Tmax) and minimum temperature (Tmin) were measured daily using a Davis weather station (Davis Vantage Pro 2 Weather Station) installed at the experimental site.

2.3. Experimental design and treatments

In this study, we evaluated the effect of two sub-surface drip (SSD)-based CA practices i.e., PCA+ and CA+ at three nitrogen rates including one control (N0 = 0, N120 = 120 and N150 = 150 kg N ha^{-1}) in comparison to furrow irrigated CA and CT with 120 kg N ha^{-1} (N120) across two cropping seasons (2018 and 2019). The three treatments under PCA+ were comprised of residue removed -permanent bed (PB) + SSD irrigation without N (N0-PCA+), 120 kg N ha^{-1} (N120-PCA+) and 150 kg N ha^{-1} (N150-PCA+). Similarly, the three treatments under CA+ were residue retained (WR)-PB + SSD without N (N0-CA+), 120 kg N ha^{-1} (N120-CA+) and 150 kg N ha^{-1} (N150-CA+). The rest treatments were furrow irrigated (FI) CA (N120-CA) and CT (N120-CT). The details of treatments adopted in this study are given in Table 1. The experiment was laid out in a randomized complete block design (RCBD) with three replications. The area of each experimental unit (plot) was 80.8 m^2.

2.4. Sub-surface drip irrigation system and irrigation management

The sub surface drip laterals having 16 mm inner diameter were installed at 20 cm soil depth by using two-row tractor operated drip laying machine with depth control mechanism developed by BISA, CIMMYT, Ludhiana, Punjab, India (Sidhu et al., 2019). The lateral depth of SSD was chosen based on the result of preliminary exploratory study on evaluation of different depths for laying laterals in MW system on PBs in the adjacent plot of the experimental field (data not reported). This study found that maize yield was similar at 15 and 20 cm lateral depths but decreased significantly at 25 cm depth. However, 20 cm of lateral depth was deemed ideal for maize on PB in order to facilitate long-term

Table 1
Details of treatments adopted.

Tillage options	Residue management	Irrigation method	Technology	N applied (kg ha^{-1})	Treatment notation
Permanent Bed (PB)	Residue removed (No residue; NR)	Subsurface drip (SSD) irrigation	PCA+ (Partial CA+SSD)	0	N0-PCA+
PB	NR	SSD		120	N120-PCA+
PB	NR	SSD		150	N150-PCA+
PB	25% previous wheat residue retention (With residue; WR)	SSD	CA+ (Full CA+SSD)	0	N0-CA+
PB	WR	SSD		120	N120-CA+
PB	WR	SSD		150	N150-CA+
PB	WR	Furrow irrigation (FI)	CA (Full CA +FI)	120	N120-CA
Conventional Tillage (CT)	Fresh bed without residue (NR)	FI	CT (CT +FI)	120	N120-CT

tillage operations. The laterals used in this study had line-sourced emitters spaced at 30 cm apart with a capacity of 2.0 L h^{-1} at a pressure of 135 kPa for the entire wetting of a plot area (~81 m^2). The laterals are 67.5 cm apart (compatible with bed width) and placed at 20 cm depth in the center of each bed, so each lateral served one row of maize (Fig. 1). The drip system was fitted with hydro-cyclone filter and screen filter (100-micron mesh size) for filtration of groundwater. Venturi injectors were used for fertigation in sub-surface drip (SSD) plots and the required suction was developed by upstream and downstream pressure difference. In SSD plots irrigation was scheduled based on soil matric potential using tensiometers monitored with a SoilSpec® vacuum gauge installed at 20 cm depth in between two rows at the center of each plot. Tensiometers installed as per Gupta et al. (2016) were regularly read each morning between 9:00–10:00 a.m. The maize crop under SSD plots were irrigated when soil moisture potential (SMP) decreased to -50 ± 1 kPa till the crop reached physiological maturity. The SSD plots received 9 and 14 irrigations (each of 10 mm) in 2018 and 2019, respectively, which amounted to 90 and 140 mm of irrigation water in total. Sidhu et al. (2019) can be refereed for further details about the SSD system. In traditional furrow irrigated plots, a total of 200 and 300 mm water (each of 50 mm) was applied based on critical crop growth stage-based scheduling approach. Irrigation was avoided when sufficient rainfall occurred at any critical crop growth stage. Due to the comparatively good and evenly distributed rainfall during the 2018 cropping period, a total of four irrigations were applied at the 6-leaf, knee-high, 50% silking, and dough stage. In contrast, the 2019 period received 33% less rainfall than the previous season, necessitating the use of 6 irrigations. One irrigation was given at 5 DAS, and the other five were scheduled at 6 leaf, late knee-high, tasseling, 50% silking, and dough stages, respectively. The volume of water applied for each irrigation was measured with the help of water meter (Dasmesh Mechanical Works, Punjab, India) fitted to the delivery pipe close to the experimental plots.

2.5. Crop management

After installation of subsurface drip lines, beds (PB) were formed in *kharif*, 2014 using a 4-wheel drive tractor operated bed planter. The same beds were kept undisturbed and maintained as permanent beds (PB) during succeeding crop seasons. The mid-furrow to mid-furrow widths of the beds were 67.5 cm, while the flat tops width and furrow depths were, 37 and 15 cm, respectively (Fig. 1). Permanent beds were reshaped once a year and crop were sown using multi-crop bed planter. On top of the raised bed a row of maize (hybrid-P3396) was planted with plant to plant spacing of 20 cm. In the CA and CT plots, maize was shown by double-disc planter fitted with an inclined plate seed metering

Fig. 1. Maize crop on furrow-irrigated (FI) conventionally tilled fresh-bed— CT (a); no-tilled residue retained permanent bed— CA (b); and subsurface drip fertigated PB with residue— CA+ (c).

mechanism. Maize hybrid was sown at a seed rate of 20 kg ha^{-1} in all treatments on June 15 and June 20, 2018 and 2019, respectively. On the CA+ and CA plots, approximately 25% of the residues from the preceding crops were retained, whereas all residues were removed in the PCA+ and CT plots.

A basal dose of 23.5 kg N, 60 kg P_2O_5 as DAP, was drilled along with seed at sowing to all the plots (except control or N0 plots where SSP was used instead of DAP). In addition to P_2O_5, each plot received a dose of 30 kg K_2O as MOP at the time of sowing. In drip irrigated treatments, the rest amount of N i.e., 96.5 and 126.5 kg N, were applied as urea through irrigation (fertigation) at 15-day interval in 4-equal split starting at 21 days after sowing (DAS). The remaining 96.5 kg N for CA and CT was top-dressed in two equal splits at knee-high and pre-tasselling stage of maize.

2.6. Measured and calculated parameters

2.6.1. Fractional intercepted photosynthetic active radiation

Photosynthetically active radiation (PAR) was measured by using a line quantum sensor LI-191SA (LICOR Inc., Lin184 coln, NE, USA) with a data logger. The incident solar radiation received (I_0) above the canopy was measured by aligning the sensor to face the sky. The transmitted radiation (I_t) through the canopy were measured by keeping the sensor just above the soil facing the canopy coverage. The fractional intercepted PAR (fIPAR) was calculated using the following equation (Nobel, 1980; Rai et al., 2019).

$$\mathrm{fIPAR} = \frac{\mathrm{I0} - \mathrm{It}}{\mathrm{I0}} \tag{1}$$

2.6.2. Leaf area index

A Portable Leaf Area Meter (LI-COR 3000) was used to measure the area of the leaves. Five representative plants from each plot were tagged and individual plant's leaf area was measured at periodic interval beginning 20 days after sowing (DAS). To measure leaf area, the scanning head of the instrument was fixed over each leaf's petiole and was passed through the leaves. The leaf area from 5 plants were averaged and expressed as leaf area per plant. The final leaf area index (LAI) was calculated using the following formula:

$$\mathrm{LAI} = \frac{\text{Total leaf } area(\mathrm{cm}^2\ \mathrm{plant}^{-1})}{\text{Ground } area(\text{spacing},\ \mathrm{cm}^2\ \mathrm{plant}^{-1})} \tag{2}$$

2.6.3. Plant nitrogen analysis, nitrogen uptake and N remobilization

The collected plant samples were first allowed to dry in the sun before being dried in a hot air oven at 60̊C until a consistent moisture was obtained. The oven-dried samples of maize were grounded by Retsch mixer mill MM 400 and used for nitrogen analysis. Nitrogen content (N) in stover and grain were determined by CHNS analyser (Euro EA-3000). The N uptake in grain and stover were computed by multiplying N content with respective yields.

The vegetative stage N uptake (VN) is basically N accumulated in biomass till the end of the vegetative stage and was calculated by using following formula:

$$\text{VN } uptake = \text{Total biomass produced till the end of vegetative } stage \times \text{N } content(\%) \text{ in } biomass \tag{3}$$

The remobilized VN into grain were calculated by balance method (Ciampitti and Vyn, 2011):

$$\text{Remobilized VN into } grain = \text{VN } uptake\text{–Stover N } uptake \text{ at } harvest \tag{4}$$

2.6.4. Nitrogen use efficiency and water productivity

In this study nitrogen use efficiency was measured by two ways i.e., apparent N recovery (AR_N), agronomic efficiency (AE_N). To calculate these efficiencies the following formulae were used:

$$\mathrm{AR_N} = \frac{\mathrm{TU_N} - \mathrm{CU_N}}{\mathrm{AF_N}} \times 100 \tag{5}$$

$$\mathrm{AE_N} = \frac{\mathrm{GY_F} - \mathrm{GY_C}}{\mathrm{AF_N}} \times 100 \tag{6}$$

Where, TU_N is the total N uptake (grain + stover) from fertilized plot (kg ha^{-1}), CU_N is the total (grain + Stover) N uptake from unfertilized control plot (kg ha^{-1}), AF_N is the amount of applied fertilizer N (kg ha^{-1}), GY_F is the grain yield in fertilized plot (kg ha^{-1}), and GY_C is the grain yield in unfertilized (control) plot (kg ha^{-1}). The water productivity (WP) was computed as the ratio of maize grain yield to the amount of water use, expressed in kg m^{-3}. Both the total water use and irrigation water applied were used as denominator for computation of WP (Pereira et al., 2012; Çetin and Kara, 2019). This results in two different WP indicators described in Eqs. 7 and 8.

$$\text{Total water } productivity\ (\mathrm{WP_{Total}}) = \frac{\text{Grain } yield}{\text{Total } water(\text{Rainfall} + \text{Irrigation}) \text{ use}} \tag{7}$$

$$\text{Irrigation water } productivity(\mathrm{WP_{Irrig}}) = \frac{\text{Grain } yield}{\text{Irrigation water } use} \tag{8}$$

2.6.5. Measurement of photosynthesis and transpiration rate

Photosynthesis rate (P_N, µmol CO_2 m^{-2} s^{-1}) and transpiration rate (T_N, nmol H_2O m^{-2} s^{-1}) were measured at two stages viz, knee high (34 DAS) and silking stage (62 DAS) in vivo using a photosynthetic system (LI-6400, LICOR, USA) under saturated light conditions (photosynthetically active radiation was set as 1200 µmol m^{-2} s^{-1}). At the knee-high stage, five plants from each plot were chosen at random, and one fully expanded youngest leaf from each individual was measured. The same plants were then tagged separately for subsequent measurement at the silking stage. During the silking stage, readings were taken from the cob leaf (immature cob) of each plant that had previously been tagged. The measurements were taken between 11.00 AM to 11.30 AM. The ambient CO_2 level was 380 ppm and the air temperature was 35̊C. The leaves were enclosed in the chamber, and the net exchange of CO_2 between leaf and the atmosphere was computed. The P_N and T_N were calculated by the Infrared Gas Analyzer's (IRGA's) inbuilt microcomputer using this rate of change and other factors such as the leaf area enclosed, the volume of enclosure, and the temperature (Anand et al., 2007; Pandey et al., 2017).

2.6.6. Specific leaf nitrogen, photosynthetic nitrogen and water use efficiency

Following the photosynthetic measurements, the area of each leaf was measured using the same Portable Leaf Area Meter. The leaves were then excised and fresh mass were also recorded. Finally, the leaves were sliced and representative samples were dried to a constant mass to estimate dry mass and N content. The leaf N content was determined using the CHNS elemental analyser (EURO EA elemental analyser, Polo Technologies, Pavia). The specific leaf nitrogen (SLN) was calculated at the panicle initiation (PI) stage (when maximum leaf expansion is expected) from N content and leaf area of dry mass (Allison et al., 1997). SLN was calculated using Eq. (8) and expressed as mmol N m^{-2}.

$$\mathrm{SLN} = \frac{\text{Leaf } weight \times \text{N } concentration}{\text{Leaf } area} \tag{9}$$

Photosynthetic nitrogen use efficiency (PNUE), the ratio of net photosynthetic rate (P_N) to leaf N content, is an important parameter in determining the response of leaf N to carbon exchange rate. The photosynthetic-NUE (PNUE) (nmol CO_2 $mmol^{-1}$ N s^{-1}) was computed according to (Anand et al., 2007):

$$PNUE = \frac{\text{Rate } of\ photosynthesis}{\text{Specific leaf nitrogen } content} \quad (10)$$

Leaves are the organ completing the processes of both water transpiration and CO_2 assimilation. Photosynthetic water use efficiency (PWUE; μmol CO_2 $mmol^{-1}$ H_2O) is often used to characterize the process. The PWUE was estimated using Eq. (10) (Guo et al., 2016).

$$PWUE = \frac{\text{Rate of } photosynthesis}{\text{Rate of } transpiration} \quad (11)$$

2.6.7. Biomass accumulation, yield attributes, grain yield and protein yield

Dry matter accumulation was measured on a regular basis by uprooting three maize plants from each plot. The collected plant samples were air dried for 7–8 days before being oven dried at 65 °C for 2 days to achieve a constant weight, which was expressed as g of dry matter per plant. The yield attributes, viz., the number of cobs per hectare, cob length (cm), cob girth (cm), the number of grains per row and cob, and 100-grains weight were estimated using standard protocol as described in Parihar et al. (2018a). For recording crop yield, two border rows from both the border directions (along the row) and 0.5 m in perpendicular direction across the row (length wise) were excluded to harvest the net plot area. All cobs from each net plot were sun dried and threshed after separating the stover and removing the husk and silk. The final grain yield was adjusted at 14.5% moisture and was expressed in t ha^{-1}. The maize stover was cut from ground level and weighed after sun drying. Thus, the weight of total harvested produce (cob + stover) from the net plot was recorded and expressed as biological yield (t ha^{-1}). The protein content of the maize crop was determined by multiplying the estimated nitrogen content by the standard factor of 6.25, as recommended by FAO (2003), Merrill and Watt (1973). The protein yield was then calculated by multiplying the grain yield by the protein content.

2.7. Economic analysis

Partial budgeting was used to calculate the economics of the SDI system, as explained by Sidhu et al. (2019), after taking into account the 80% subsidy provided by the Government of India on the actual cost (US $ 3477.90 ha^{-1}). The annual depreciation was calculated using the straight-line depreciation method after considering a salvage value of 10% and 15-years useful life span of the SSD system (Sidhu et al., 2019). As a result, the final cost incurred for SSD installation for a single crop in the MW system came to US$ 20.87. Across the study years (2018 and 2019), gross returns (GR), and net returns (NR) were calculated on the basis of inputs used and outputs obtained considering the incurred variable cost. The cost of human labor was calculated considering the eight-hour person-day as defined by Indian labor law. In addition, the amount of machinery time (hours per hectare) required to perform a specific on-farm operation was calculated. The total cost of all on-farm operations was calculated by adding the cost, time, diesel and electricity used to complete each operation. Summing the input costs yielded the total variable cost (TVC). The gross returns (GR) included income from the sale of grain and stover of maize. The GR was calculated by using market minimum support price (MSP) for maize grain. The TVC (including annual depreciation cost – US$ 20.87) was subtracted from the GR to determine the NR. Fixed costs such as land value and interest were not included in this economic analysis. All economic analysis was conducted in Indian rupees (INR), which were then converted into US$.

2.8. Statistical analysis

The ANOVA was conducted for all the agronomic data, viz, N uptake, N use efficiency, yield attributes, yield and biological yield using the statistical analysis system (SAS Institute, Cary, NC) for RCBD. If ANOVA was found significant, the differences between treatment means were compared using the LSD test at $P < 0.05$ (Gomez and Gomez, 1984).

3. Results

3.1. Weather

Total rainfall during the 2018 maize crop (June 15 to October 10) was 723.9 mm, almost half of which was received in July and September (Fig. 2a), higher than the long-term June-October average of 600.6 mm. The 2019 maize season was drier than the previous year, with nearly half of the rainfall falling in August (Fig. 2a), and total cropping period (June 20 to October 13) rainfall was 488.2 mm. Monthly pan evaporation of both cropping season tended to be similar or lower than the long-term average, except for much lower values in October each year and higher values in June. During 2018, mean monthly maximum (Tmax) and minimum (Tmin) temperatures were lower than or comparable to long-term values (Fig. 2b). Tmax and Tmin were similar to and higher than the corresponding long-term maximum and minimum averages in 2019. The highest Tmax and lowest Tmin of both seasons were recorded in June and October, respectively.

3.2. Leaf area index and fractional intercepted photosynthetically active radiation

The two-year mean leaf area index (LAI) during 30, 60, 75 and 105 DAS significantly varied among the treatments (Fig. 3). Across the treatments the LAI increased till 60–75 DAS and attained the plateau. At 30 DAS, the LAI did not vary among the N fertilized treatments. During the active growth phase, N150-CA+ had the highest LAI, followed by N150-PCA+ , N120-CA+ , and N120-PCA+ , respectively. However, the LAI in N150-PCA+ and N120-CA+ was comparable. Throughout the cropping season, similar LAI was recorded between furrow irrigated CA (N120-CA) and CT (N120-CT) plots. At 75 DAS, the LAI in the CA+ -based N150-CA+ treatment was nearly 1.2 times that of the furrow irrigated N120-CA and N120-CT treatments. The CA+ plots with residue retention had higher LAI than residue removed PCA+ plots.

Fractional intercepted photosynthetically active radiation (fIPAR) was significantly influenced by tillage, irrigation, nitrogen and residue management options (Fig. 4). The maximum light interception by crop canopy was observed between 55 and 70 DAS in all the treatments, coinciding with the beginning of the reproductive phase of the maize. During this period the largest fIPAR (0.90–0.95) were recorded in N150-CA+ plots followed by N150-PCA+ (0.86–0.90), N120-CA+ (0.81–0.86) and N120-PCA+ (0.77–0.82). On an average, residue retained SSD (CA+) plots intercepted more radiation than residue removed (PCA+) plots. The fIPAR in CT and CA-based plots with 120 kg N ha^{-1} were comparable. During the peak growth period, SSD adoption improved light interception by a minimum of 11% over furrow irrigation.

3.3. Photosynthetic parameters

The tillage, residue, N and irrigation management practices significantly ($P < 0.05$) influenced the rate of photosynthesis (P_N) and transpiration (T_N) (Table 2). The P_N was found to be higher in N150-CA+ during knee-high and silking (24 and 34 mol CO_2 m^{-2} s^{-1}, respectively), which was comparable to N150-PCA+ and N120-CA+ and 18% and 14% higher than N120-PCA+ . The P_N under N120-CA+ was 12% and 3% higher than furrow irrigated treatments (N120-CA and N120-CT) at knee-high and silking stages, respectively. Similarly, P_N of N150-CA+ was 22% and 6% higher at knee-high and silking stage, respectively, as compared to the CA and CT. At silking, residue retention had a greater effect on P_N in the CA+ plots than in the PCA+ plots where residues were removed. The effect was more pronounced at higher N dose (150 kg ha^{-1}). At both the knee-high and silking stages, the photosynthetic nitrogen use efficiency (PNUE) was similar in the sub-surface drip irrigated CA+ and PCA+ treatments (Table 2). The SSD irrigated N150-CA+ treatment had the highest PNUE (90.55 and 311.0

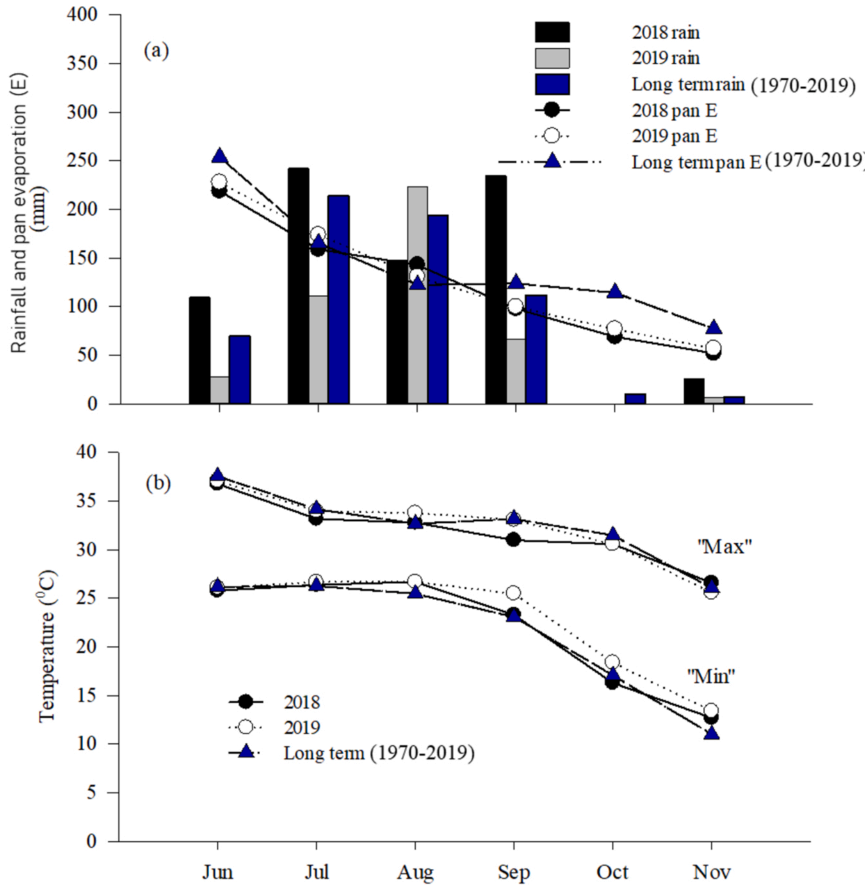

Fig. 2. Meteorological parameters during the cropping period (2018 and 2019) and long-term (1970–2019).

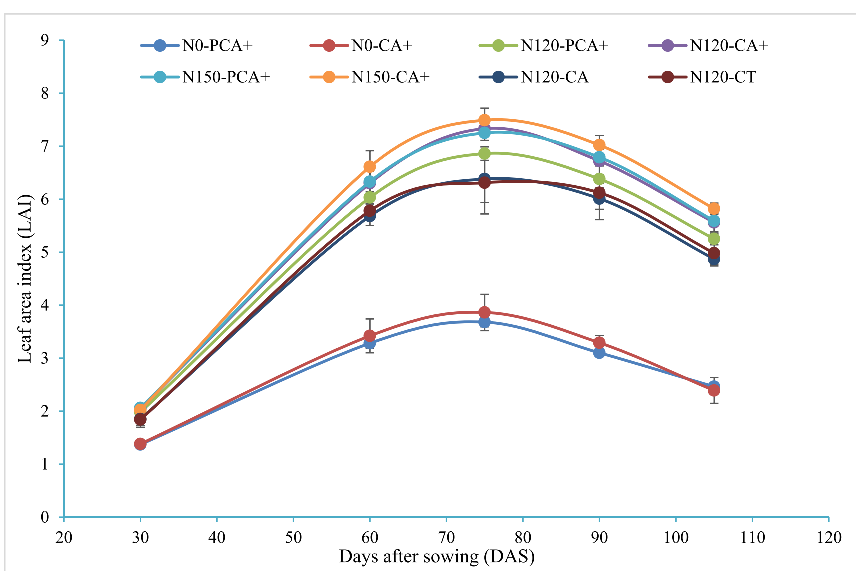

Fig. 3. Effect of different tillage, nitrogen doses and residue and irrigation management practices on leaf area index of maize (2-year mean basis). Vertical bars are standard error (SE) within each treatment. *Refer to Table 1 for treatment details.

μmol CO_2 g^{-1} N s^{-1}), which was 26.18% and 10.50% higher than the furrow irrigated N120-CA and N120-CT at knee high and silking, respectively. At the knee-high stage, PNUE was similar in furrow irrigated CA and CT-based plots, but at the silking stage, it was ~22% higher in CA-based plots.

At knee-high stage, the transpiration rate (T_N) in N fertigated PCA+ and CA+ treatments was 15.33% higher than in furrow-irrigated CA and CT, respectively (Table 2). However, at this stage, the T_N did not differ significantly between the CA+ and PCA+ treatments. The T_N in the residue retained and residue removed plots was nearly identical at both the stages. At the silking stage, the N150-CA+ treatment had the highest T_N (7.81 mmol H_2O m^{-2} s^{-1}), which was statistically at par to the

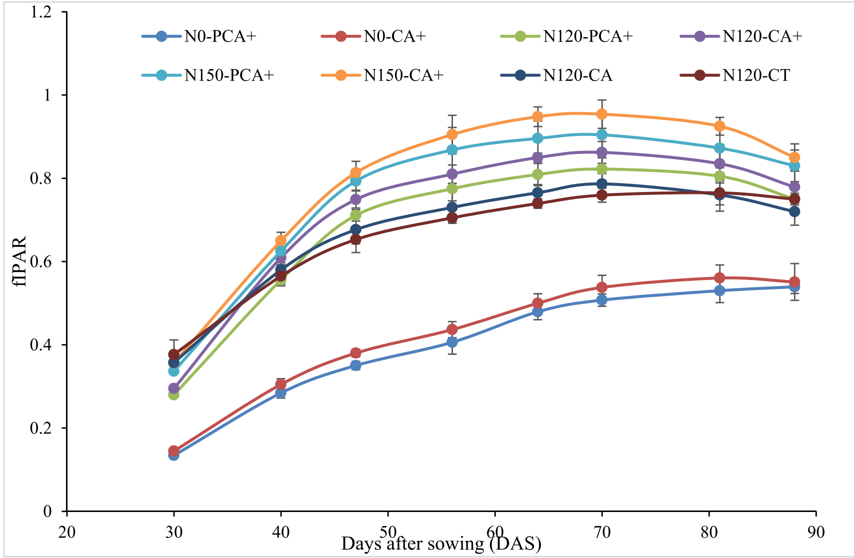

Fig. 4. Effect of different tillage, nitrogen doses and residue and irrigation management on fractional intercepted photosynthetically active radiation (fIPAR) of maize. Vertical bars are standard error (SE) within each treatment. *Refer to Table 1 for treatment details .

Table 2
Effect of different tillage, residue, N doses and irrigation management practices on rate of transpiration, photosynthesis, photosynthetic use efficiency of water (PWUE) and nitrogen (PNUE) of maize (2-year mean basis).

[a]Treatments	Rate of photosynthesis (μmol CO_2 m^{-2} s^{-1})		Rate of transpiration (mmol H_2O m^{-2} s^{-1})		PWUE (μmol CO_2 $mmol^{-1}$ H_2O)		PNUE (nmol CO_2 $mmol^{-1}$ N s^{-1})	
	Knee high	Silking	Knee high	Silking	Knee high	Silking	Knee high	Silking
N0-PCA+	14.93d	19.67c	4.93c	5.53d	3.03ab	3.59c	83.63bc	270.03cd
N0-CA+	15.58d	20.59c	5.03c	5.81d	3.11a	3.57bc	82.65bc	255.07d
N120-PCA+	20.27 bc	30.33 bc	8.33a	6.70bc	2.44d	4.54ab	79.73c	290.80b
N120-CA+	21.94ab	30.53bc	8.36a	6.95b	2.63 cd	4.41bc	86.53ab	284.97bc
N150-PCA+	22.82a	32.12ab	8.43a	7.51a	2.73bcd	4.30c	83.43bc	284.60bc
N150-CA+	23.87a	34.43a	8.41a	7.81a	2.83abc	4.43abc	90.55a	311.0a
N120-CA	18.66c	29.87bc	7.28b	6.50c	2.58 cd	4.62a	72.96d	309.76a
N120-CT	20.04c	29.65c	7.26b	6.62bc	2.77bcd	4.50ab	70.50d	253.09d

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at $P < 0.05$) according to least significant difference test.

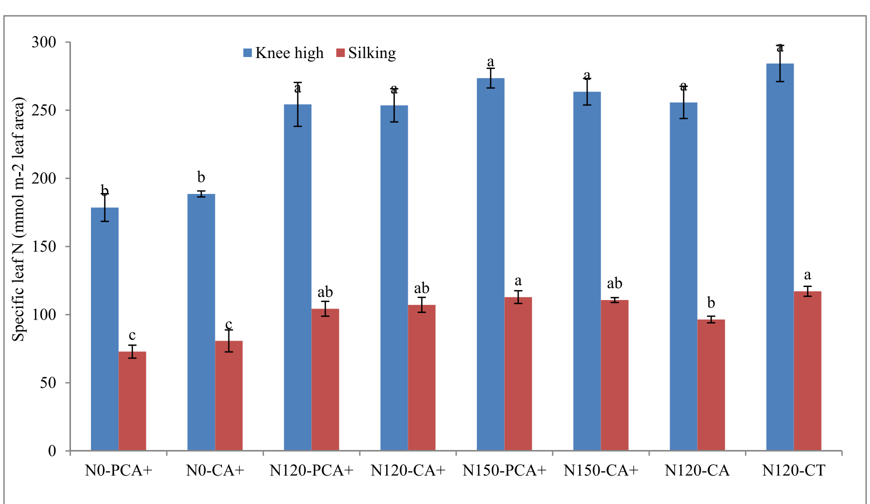

Fig. 5. Effect of different tillage, nitrogen (N) doses and residue and irrigation management practices on specific leaf N content of maize (2-year mean basis). Vertical bars are standard error (SE) within each treatment and bars followed by different letter among treatments are significantly different (at $P < 0.05$) according to least significant difference test. *Refer to Table 1 for treatment details.

N150-PCA+ (7.51 mmol H_2O m^{-2} s^{-1}) and 19% higher than furrow irrigated CA and CT treatments. At the knee-high stage, the photosynthetic water use efficiency (PWUE) did not differ across different crop establishment options, residue, N and irrigation management practices except for N120-PCA+ , which had lowest PWUE (Table 2). The PWUE was greater in control treatments than in the N fertilized treatments at knee-high stage. However, among N fertilized treatments, N150-CA+ had the highest knee-high stage PWUE. At silking, the PWUE was highest in CA treatment (N120-CA; 4.62 μmol CO_2 $mmol^{-1}$ H_2O), which was statistically similar to N120-PCA+ , N150-CA+ , and N120-CT.

All N fertilized treatments had statistically similar specific leaf nitrogen (SLN) content at knee-high stage, ranging from 253.6 to 284 mmol N m^{-2}. The SLN under N120-CT was 11% higher than N120-CA treatment at knee-high (Fig. 5). Similar to tasseling, the SLN content at silking was alike in all N fertilized treatment except N120-CA, which had lowest SLN. At same N application rate (120 kg ha^{-1}), the SLN in CA+ based N120-CA+ was 11% and 9% higher than furrow irrigated N120-CA and N120-CT, respectively.

3.4. *Yield attributing characters*

Cob length and grains per cob were significantly ($P < 0.05$) affected by tillage, residue, N and irrigation management options (Table 3a & Table 3b). The cob length and grains per cob were similar ($P > 0.05$) in PCA+ , CA+ and CA plots. Apart from control plots, the lowest cob length and grains per cob were observed in N120-CT (19.5 cm and 517; two-year mean), while the highest was observed in N150-CA+ treatment (22.2 cm and 604 grains cob^{-1}). The average cob length and grains per cob in N150-CA+ plots were 14% and 17% higher than N120-CT, respectively. SSD treatments with 120 kg N, i.e., N120-PCA+ and N120-CA+ , had 6% longer/higher average cob length and grains per cob than N120-CT. The CA+ plots recorded 7% longer cob length and 5% more grains per cob than the PCA+ plots. However, among all N fertilized treatments, the effect of tillage, residue, N rate, and irrigation on cob girth, grains per row, 100 grain weight, and cobs per hectare was non-significant (Table 3b).

3.5. *Biomass accumulation and biological yield*

The dry matter accumulation was faster during the first 60 days, then the biomass increased at a slower rate (Fig. 6). The N150-CA+ plots showed largest (2-years mean) biomass accumulation which was nearly similar to biomass production under N150-PCA+ . Among the N fertilized treatments, N120-CT had the lowest biomass accumulation, which was statistically at par with N120-CA. Surface residue retention had a significant positive effect on biomass accumulation (Fig. 6). The biological yield was 31% and 36% higher in the N150-CA+ than in furrow-irrigated N120-CA and N120-CT treatments, respectively (Table 4). Similarly, at the same N application rate of 120 kg ha^{-1}, N120-CA+ produced 17% and 22% higher biological yield than N120-CA and N120-CT. On an average, CA+ based plots produced 5% higher biological yield than PCA+ based plots. Further, the biological yield of the N120-CA treatment was 4.2% higher than N120-CT treatment.

3.6. *Grain and stover yields*

Maize grain yield (GY) was significantly affected by ($P < 0.05$) tillage, residue, N and irrigation management options (Table 4). The GY of all SSD fertigated CA+ and PCA+ treatments were significantly higher than that of the N120-CA and N120-CT plots. Across the years, CA+ based N150-PCA+ (8.54 and 7.79 t ha^{-1}) and N150-CA+ (8.17 and 8.23 t ha^{-1}) treatments had similar GY, which was significantly higher than other CA+ and CA, CT treatments. The CA+ based N150-CA+ treatment produced highest two-year mean grain yield (8.20 t ha^{-1}) and was statistically at par with N150-PCA+ (8.17 t ha^{-1}). The maize grain yield was 27% and 30% higher under N150-CA+ than the furrow irrigated N120-CA (6.46 t ha^{-1}) and N120-CT (6.33 t ha^{-1}), respectively. At the same N level, maize yields in N120-CA+ were 16% and 18% higher as compared to the N120-CA and N120-CT, respectively. On average, CA+ based plots had higher GY than PCA+ based plots. Tillage, residue, N, and irrigation management options all had a significant ($P < 0.05$) effect on stover yield (Table 4). Across the years, all N fertigated CA+ and PCA+ plots produced more stover yield than the furrow-irrigated N120-CA and N120-CT plots. Similar to the GY, highest stover yield was recorded under N150-CA+ , which was 33% and 38% higher than CA and CT, respectively.

3.7. *Grain and stover nitrogen uptake and protein yield*

Significant differences ($P < 0.05$) in both grain and stover N uptake were observed between SSD fertigated and conventionally N broadcasted furrow irrigated treatments i.e., N120-CA and N120-CT (Table 5). N uptake was higher in treatments with higher N dose (150 kg ha^{-1}). The N150-CA+ treatment had the highest two-year mean grain N uptake (113 kg ha^{-1}) that was statistically comparable to the PCA+ treatment–N150-PCA+ (108 kg ha^{-1}).

Among N fertilized treatments, significantly ($P < 0.05$) lower grain N uptake was recorded in furrow irrigated N120-CA and N120-CT, which showed a similar uptake pattern (Table 5). The average uptake of these treatments was 39% lower than N150-CA+ treatment. On an average, CA+ treatments recorded 29% higher grain N uptake than the CA and CT. Similar to grain N uptake, across the years SSD fertigated PCA+ and CA+ treatments recorded higher stover N uptake than CA and CT. At the same N level, the uptake of PCA+ and CA+ was statistically equal. The grain N content did not differ statistically ($P < 0.05$) between treatments or years (data not reported). However, grain-protein yield ranged significantly ($P < 0.05$) from 48.78 to 72.9 kg ha^{-1} depending on tillage, residue, irrigation method, and N

Table 3a
Effect of different tillage, residue, N doses, and irrigation management practices on yield attributing characters of maize (during 5th-2018 and 6th-2019 years of experimentation).

[a]Treatments	Cobs ('000 ha^{-1})			Cob length (cm)			Cob girth (cm)		
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
N0-PCA+	53.2b	51.7b	52.5b	12.2c	12.1c	12.2c	10.6b	10.7b	10.7b
N0-CA+	53.8b	52.6b	53.2b	13.8c	13.7c	13.8c	10.7b	10.7b	10.7b
N120-PCA+	72.5a	70.4a	71.4a	20.4ab	20.3ab	20.4ab	14.6a	14.7a	14.7a
N120-CA+	73.2a	71.1a	72.2a	20.9ab	20.8ab	20.9ab	14.7a	14.8a	14.7a
N150-PCA+	74.6a	71.9a	73.2a	22.0a	21.8ab	21.9ab	14.7a	14.8a	14.8a
N150-CA+	74.5a	72.5a	73.5a	22.3a	22.1a	22.2a	14.6a	14.7a	14.7 a
N120-CA	72.6a	69.4a	71.0a	20.3ab	20.1ab	20.2ab	14.3a	14.4a	14.3a
N120-CT	69.2a	69.2a	69.2a	19.6b	19.5b	19.5b	14.5a	14.6a	14.5a

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at $P < 0.05$) according to least significant difference test.

Table 3b
Effect of different tillage, residue, N doses and irrigation management practices on yield attributing characters of maize (during 5th-2018 and 6th-2019 years of experimentation).

[a]Treatments	Grains row^{-1}			Grains cob^{-1}			100- grain weight (g)		
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
N0-PCA+	17.9b	17.4b	17.7b	191.0c	185.6c	188.3c	19.2c	18.8c	19.0c
N0-CA+	18.8b	18.2b	18.5b	213.5c	207.5c	210.5c	19.6bc	19.1bc	19.3bc
N120-PCA+	35.0a	34.0a	34.5a	545.5ab	530.4ab	537.9ab	22.7a	22.2a	22.5a
N120-CA+	35.9a	34.9a	35.4a	571.8ab	555.3ab	563.6ab	23.2a	22.7a	23.0a
N150-PCA+	36.2a	35.1a	35.7a	578.6ab	561.1ab	569.9ab	23.8a	23.3a	23.5a
N150-CA+	37.1a	35.9a	36.5a	613.4a	594.6a	604.0a	24.4a	23.8a	24.1a
N120-CA	34.7a	33.7a	34.2a	539.5ab	524.8ab	532.2ab	22.6ab	22.0ab	22.3ab
N120-CT	34.3a	33.2a	33.8a	525.0b	510.0b	517.5b	22.4ab	21.9ab	22.1ab

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at $P < 0.05$) according to least significant difference test.

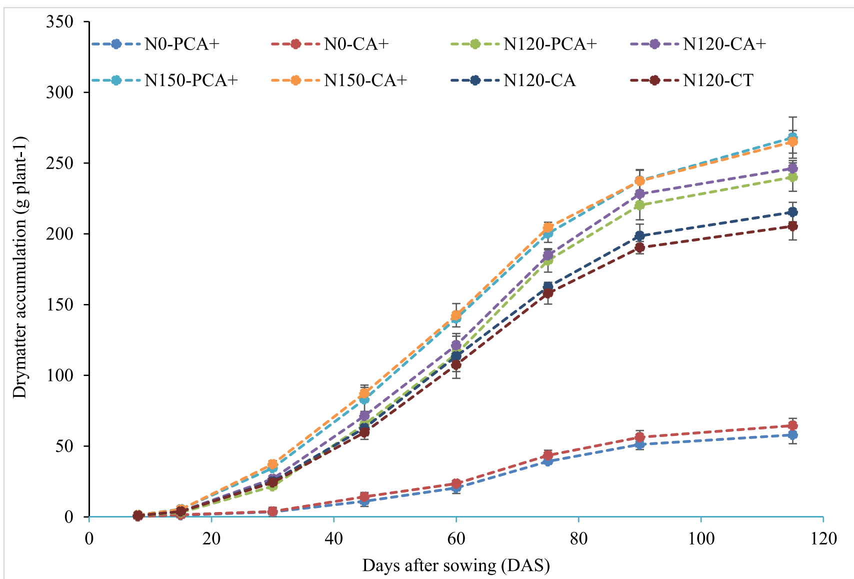

Fig. 6. Effect of different tillage, nitrogen doses and residue and irrigation management practices on biomass accumulation of maize (2-year mean basis). Vertical bars are standard error (SE) within each treatment. *Refer to Table 1 for treatment details.

Table 4
Effect of different tillage, residue, N doses and irrigation management practices on yields of maize (during 5th-2018 and 6th-2019 years of experimentation).

[a]Treatments	Grain yield (t ha^{-1})			Stover yield (t ha^{-1})			Biological yield (t ha^{-1})
	2018	2019	Mean	2018	2019	Mean	2-year mean
N0-PCA+	2.40d	1.60d	2.00d	3.42d	2.32d	2.87e	5.33f
N0-CA+	2.88d	1.79d	2.34d	4.22d	2.63d	3.43e	6.25f
N120-PCA+	7.43bc	6.88bc	7.15b	10.49bc	9.82bc	10.15bcd	18.89 cd
N120-CA+	7.54bc	7.38ab	7.46b	10.86abc	10.52b	10.69abc	19.98bc
N150-PCA+	8.54a	7.79ab	8.17a	11.78ab	10.77ab	11.27ab	21.46ab
N150-CA+	8.17ab	8.23a	8.20a	12.22a	12.26a	12.24a	22.38a
N120-CA	6.77c	6.16c	6.46c	9.78c	8.68c	9.23 cd	17.12de
N120-CT	6.65c	6.01c	6.33c	9.30c	8.40c	8.85d	16.43e

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at $P < 0.05$) according to least significant difference test.

application (Fig. 7). Protein yield was higher in SSD fertigated treatments than in furrow irrigated CA and CT. The highest protein yield (70.42 kg ha^{-1}, two year mean) was obtained under N150-CA+ , which was comparable to N150-PCA+ (67.38 kg ha^{-1}) and N120-CA+ (60.29 kg ha^{-1}). Even at same N level (120 kg ha^{-1}) SSD treatment—N120-PCA+ and N120-CA+ produced 19% and 14% higher protein yields, respectively, than the mean yield of N120-CA and N120-CT.

3.8. *Vegetative stage N uptake and its remobilization into grain*

The vegetative stage N uptake (VN_U) and its remobilization into grain was significantly affected by tillage, residue, N and irrigation management (Fig. 8). VN_U was 36% and 33% higher ($P < 0.05$) under N fertigated PCA+ and CA+ treatments compared to furrow irrigated treatments (CA and CT). The Highest VN_U was found in N150-PCA+ (110 kg ha^{-1}), which was statistically at par with N150-CA+ (107 kg ha^{-}

Table 5
Nitrogen uptake in grain and stover and 2-year mean % of vegetative N remobilized in maize grain as affected by different tillage, residue, N doses and irrigation management practices (during 5th-2018 and 6th-2019 years of experimentation).

[a]Treatments	N uptake ($kg\ ha^{-1}$)					
	Grain			Stover		
	2018	2019	Mean	2018	2019	Mean
N0-PCA+	30.8d	21.1d	26.0e	14.7c	10.1d	12.4d
N0-CA+	36.5d	23.2d	29.8e	17.4c	11.1d	14.2d
N120-PCA+	95.7bc	90.7bc	93.2 cd	33.6b	32.0b	32.8b
N120-CA+	96.5bc	96.5ab	96.5bc	32.3b	31.8b	32.1bc
N150-PCA+	106.3ab	109.3a	107.8ab	40.1a	41.0a	40.6a
N150-CA+	116.6a	108.7a	112.7a	42.2a	39.2a	40.7a
N120-CA	84.6c	78.4c	81.5d	30.2b	27.3bc	28.7bc
N120-CT	84.4c	78.1c	81.2d	29.4b	26.8c	28.1c

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at P < 0.05) according to least significant difference test.

^{1}). The SSD fertigated plots with 120 kg N ha^{-1} i.e., N120-CA+ and N120-PCA+ recorded 13% and 18% higher VN_U than CA (N120-CA) and CT (N120-CT), respectively. Similarly, the average VN_U increase in N150-CA+ and N150-PCA+ treatments was 45% and 52%, compared to CA and CT. A similar pattern was also observed for remobilized N (Fig. 8). The remobilized N from vegetative stage in N150-CA+ , N150-PCA+ , N120-CA+ and N120-PCA+ was 48%, 56%, 18% and 15% higher than the average of furrow irrigated CA (46 kg ha^{-1}) and CT (43.3 kg ha^{-1}) averages, respectively.

3.9. Nitrogen use efficiency

The CA+ and PCA+ treatments increased two-year mean agronomic N use efficiency (AE_N) by 8.32–19.14% and 13.63–24.89%, respectively, over CT and CA (Table 6). The highest AE_N (42.95 kg grain kg^{-1} N) was recorded in PCA+ treatment with 120 kg N, i.e., N120-PCA+ , which was nearly equal to AE_N of CA+ based N120-CA+ (42.67 kg grain kg^{-1} N). At same level of N (120 kg ha^{-1}), adoption of SSD irrigation gave additional 8.28 and 6.90 kg of grains per kg of applied N over furrow irrigated CA and CT. Across two-year of experimentation, the apparent N recovery (AR_N) was increased by 11.80–19.29% and 5.57–16.62% in SSD based CA+ and PCA+ treatments than furrow irrigated CA and CT,

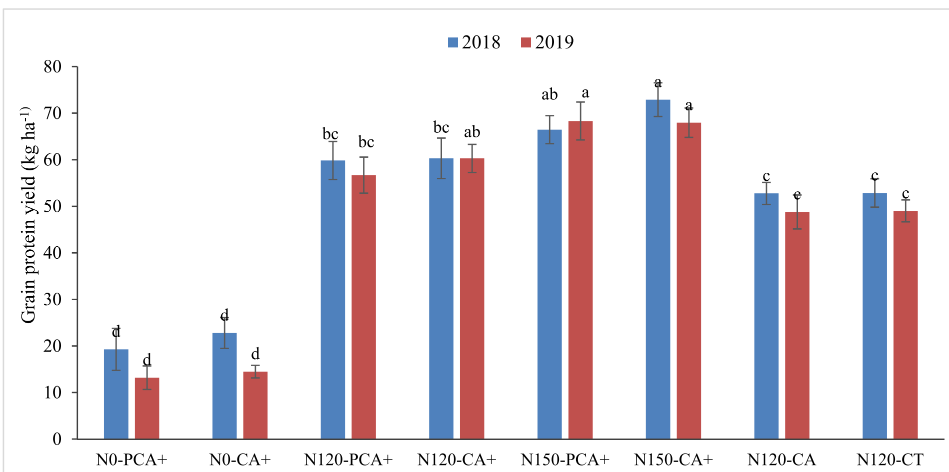

Fig. 7. Effect of different tillage, nitrogen (N) doses and residue and irrigation management practices on grain protein yield of maize. Vertical bars are standard error (SE) within each treatment and bars followed by different letter among treatments are significantly different (at P < 0.05) according to least significant difference test. *Refer to Table 1 for treatment details.

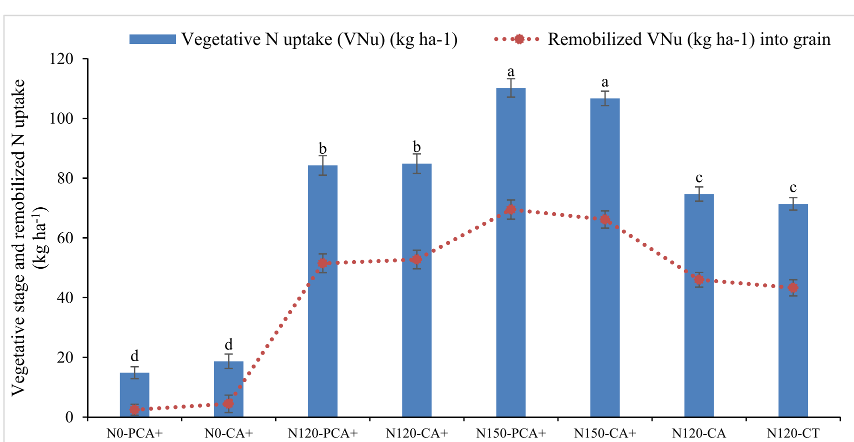

Fig. 8. Effect of different tillage, nitrogen (N) doses and residue and irrigation management practices on vegetative stage N uptake and its remobilization into grain in maize (2-year mean basis). Vertical bars are standard error (SE) within each treatment and bars followed by different letter among treatments are significantly different (at P < 0.05) according to least significant difference test. *Refer to Table 1 for treatment details.

Table 6
Nitrogen use efficiencies of maize as affected by different tillage, residue, N doses and irrigation management practices (during 5th-2018 and 6th-2019 years of experimentation).

Treatments	Agronomic efficiency (kg grain increase/kg of N applied)			Recovery Efficiency (% of applied N uptake by grain + stover)		
	2018	2019	Mean	2018	2019	Mean
N0-PCA+	-	-	-	-	-	-
N0-CA+	-	-	-	-	-	-
N120-PCA+	41.87	44.03	42.95	69.83	76.21	73.02
N120-CA+	38.81	46.53	42.67	62.45	78.37	70.41
N150-PCA+	40.93	41.29	41.11	67.28	78.20	72.74
N150-CA+	35.23	42.93	39.08	69.99	76.96	73.47
N120-CA	32.41	36.36	34.39	50.70	59.18	54.94
N120-CT	35.37	36.72	36.05	56.88	61.75	59.31

respectively (Table 6). However, the mean AR_N was similar in all SSD fertigated CA+ and PCA+ based treatments, which ranged between 70.41% and 73.47%. The AR_N of CA+ based N150-CA+ was 18.53% and 14.16% higher, respectively, than furrow irrigated N120-CA and N120-CT.

3.10. Water productivity

Across the years, total water use was affected by rainfall, whereas across the treatment the water use varied due to contrasting irrigation management practices i.e., subsurface drip irrigation (SSD) in PCA+ and CA+ treatments and conventional furrow irrigation (FI) in CA and CT (Table 7). As compared to 2018 cropping period almost 1.5 times higher amount of irrigation water was applied in SSD and FI plots during 2019. The irrigation water saving for maize production under SSD irrigated CA+ and PCA+ treatments were 55.0% and 53.3% (average 54.15%) in the years 2018 and 2019, respectively (Table 7). Water productivity (WP) was significantly ($P < 0.05$) affected by tillage, residue, N, and irrigation management practices (Table 7). The highest two-year mean irrigation water productivity (WP_{Irrig}) (7.53 kg m^{-3}) was recorded under N150-PCA+ treatment which was statistically at par with N150-CA+ (7.48 kg m^{-3}). The WP_{Irrig} of these treatments were 2.78 times greater than the average WP_{Irrig} of N120-CA (2.72 kg m^{-3}) and N120-CT (2.66 kg m^{-3}). Even at same level of N (120 kg ha^{-1}), SSD irrigated N120-CA+ produced 2.5 times more WP_{Irrig} than furrow irrigated N120-CA and N120-CT. In terms of total water productivity (WP_{Total}), treatment N150-CA+ was the most productive, followed by N150-PCA+ , N120-CA+ , and N120-PCA+ (Table 7). However, the values were less than WP_{Irrig} as rainfall was added as denominator.

3.11. Economics

Across the years, the cost of cultivation (COC) was higher in residue retained N fertilized treatments (CA+ and CA) as compared to no residue treatments (PCA+ and CT) (Table 8). Regardless of N rate, the largest net returns (NR) were observed under SSD fertigated CA+ and PCA+ based plots (Table 8). The maximum NR (US$ 1657 ha^{-1}) was observed in PCA+ based N150-PCA+ , which was statistically comparable to CA+ N150-CA+ (US$ 1622 ha^{-1}). The PCA+ based treatment, N150-PCA+ fetched 478 and 504 (average 491) US$ higher NR than N120-CA and N120-CT treatments, respectively, whereas the NR under N150-CA+ was higher by 443 and 469 (average 456) US$ than the same CA and CT, respectively. The NR under SSD-based treatments with N dose of 120 kg were also higher than the NR of CA and CT. The net benefit-cost ratio (NBCR) was significantly higher (3.04–3.91) in SSD fertigated CA+ and PCA+ treatments than conventionally broadcasted, furrow irrigated CA (2.51) and CT (2.51) treatments. Highest NBCR was observed under N150-PCA+ (3.91) treatment followed by CA+ based N150-CA+ (3.40). The average NBCR in furrow irrigated CA and CT was 1.55 and 1.51 times lower than N150-PCA+ and N150-CA+ plots, respectively. The lowest NBCR (3.04) among SSD fertigated treatments was recorded under N120-CA+ treatment, which was 21% higher than furrow irrigated N120-CA and N120-CT's NBCR (Table 8).

4. Discussion

4.1. Leaf area index, fractional intercepted photosynthetically active radiation and photosynthetic behaviour

A higher N application in a greater number of splits with drip irrigation improved the LAI under CA+ based treatments. Alike to our finding, Amanullah et al. (2010) reported a positive correlation of N rate and split with LAI and light interception. Further, retention of crop residue improved the LAI and fIPAR under CA+ based plot, as it increased the nutrient and water availability (Sandhu et al., 2019; Nayak et al., 2022). Similarly, other studies by Sampathkumar and Pandian (2012), Qin et al. (2016), and Irmak et al. (2022) have also reported a larger LAI increment under drip irrigation. Since LAI and leaf area duration (LAD) have a direct impact on the interception of incoming PAR, the larger fIPAR was observed in the SSD treatment with a LAI of 6–7, which is considered optimal for intercepting the maximum incoming radiation flux (Chanh et al., 1993; Guo et al., 2012).

The knee-high stage rate of photosynthesis (P_N) was observed higher in the N fertigated SSD plots, which was mainly due to early application of 1st N split (~24 and 32 kg N) at 21 DAS in CA+ /PCA+ based plots. On contrary, the lesser P_N under CA and CT at knee-high stage (34 DAS) was mainly due to late application of 1st N split (~48 kg N). The early N top dressing at 21 DAS in SSD treatments boosted early season crop

Table 7
Water use and water productivity (WP) of maize as affected by different tillage, residue, N doses, and irrigation management practices (during 5th-2018 and 6th-2019 years of experimentation).

aTreatments	Total water input (mm) ($RF + irrigation)		Irrigation water input (mm)		Total WP (WP_{Total}) (kg m^{-3})			Irrigation WP (WP_{Irrig}) (kg m^{-3})		
	2018	2019	2018	2019	2018	2019	Mean	2018	2019	Mean
N0-PCA+	813.9	628.2	90	140	0.30d	0.26d	0.28d	2.67c	1.14e	1.91d
N0-CA+	813.9	628.2	90	140	0.35d	0.29d	0.32d	3.20c	1.28e	2.24 cd
N120-PCA+	813.9	628.2	90	140	0.91b	1.10b	1.00b	8.25b	4.92c	6.58b
N120-CA+	813.9	628.2	90	140	0.93b	1.17ab	1.05b	8.38b	5.27 bc	6.82b
N150-PCA+	813.9	628.2	90	140	1.05a	1.24ab	1.14a	9.49a	5.57ab	7.53a
N150-CA+	813.9	628.2	90	140	1.00ab	1.31a	1.53a	9.07ab	5.88a	7.48a
N120-CA	923.9	788	200	300	0.73c	0.78c	0.76c	3.39c	2.05d	2.72c
N120-CT	923.9	788	200	300	0.72c	0.76c	0.74c	3.32c	2.00d	2.66c

$Rainfall during the cropping period of 2018 and 2019 was 724 and 488 mm, respectively.
[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at P < 0.05) according to least significant difference test.

Table 8
Economics of maize as affected by different tillage N doses and residue and irrigation management practices (during 5th-2018 and 6th-2019 years of experimentation).

aTreatments	Cost of cultivation (USD ha-1)			Net return (USD ha-1)			Net BC ratio		
	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
N0-PCA+	389	403	396	213e	14e	114d	0.55d	0.04d	0.29d
N0-CA+	406	420	413	317d	47e	182d	0.78d	0.11d	0.45d
N120-PCA+	412	426	419	1448bc	1366bc	1407b	3.51b	3.20ab	3.36b
N120-CA+	465	480	472	1425bc	1441ab	1433b	3.07bc	3.01b	3.04b
N150-PCA+	417	432	424	1719a	1595ab	1657a	4.12a	3.69a	3.91a
N150-CA+	470	485	477	1580ab	1663a	1622a	3.36b	3.43ab	3.40b
N120-CA	463	479	471	1234c	1123 cd	1179c	2.67c	2.34c	2.51c
N120-CT	452	468	460	1212c	1094d	1153c	2.68c	2.34c	2.51c

[a] For treatment detail please see Table 1. Means followed by different lowercase letter within each column are significantly different (at $P < 0.05$) according to least significant difference test.

growth and biomass accumulation at knee-high stage. In addition, a frequent N and water application based on soil moisture potential (SMP) have been shown to enhance the N and moisture availability in the root zone (Eltarabily et al., 2019; Bronson et al., 2019), resulting in increased P_N and transpiration rate (T_N) at knee-high and silking under SSD fertigated CA+ and PCA+ plots. A high regulated soil moisture levels, with minimal variation, can help reduce crop stress and improve both P_N and T_N, ultimately leading to an increase in crop yield (Patra et al., 2021a). On the other hand, with surface irrigation under CA and CT, the soil moisture and N content deplete to suboptimal level to reduce P_N and T_N (Shen et al., 2020; Umair et al., 2019). A suboptimal moisture can lead to closure of stomata, which in turn can negatively affects P_N (Kumar et al., 2011; Grassi and Magnani, 2005; Ripley et al., 2007). Moreover, keeping crop residue for a medium term together with SSD creates favourable soil environment that enhances crop growth (Habbib et al., 2020; Parihar et al., 2016b), which leads to an increase in PNUE and photosynthetic water use efficiency (PWUE). The similar value of PNUE between control and N-fertigated plots at knee-high stage was due to less P_N and lesser specific leaf nitrogen (SLN) under control, resulting in a ratio similar to the fertigated plots. However, the improvement in PNUE under all N fertigated CA+ and PCA+ plots over CA and CT is mainly because of higher rate photosynthesis. The 22% lower knee-high PNUE under CT compared to CA plots is mainly due to 1.2 times lower SLN (denominator) in CA.

4.2. Nitrogen uptake, specific leaf nitrogen, remobilization and nitrogen use efficiency

During early stages of development, plants grew predominantly in isolated form with minor competition for light. Under such condition, plant N concentration does not vary significantly with leaf area increment (Lemaire et al., 2007; Qiang et al., 2019). This might be the reason behind statistically similar SLN at knee-high under all N fertilized treatments. However, as SLN is the leaf N content per unit leaf area, we may find the source of difference in SLN by inspecting the numerical differences between treatments in leaf N content (g) and leaf area (m^2). The amplitude of specific leaf area increase was bigger than leaf N content in all N applied CA+ treatments at both knee-high stage and silking, resulting in a slightly lower SLN under CA+ compared to PCA+ treatments (Poorter and Evans, 1998; Habbib et al., 2020). In another way, the greater crop growth of CA+ caused more dilution of leaf N per unit leaf area. The same dilution effect resulted in lower SLN in CA plots compared to CT plots.

A higher N uptake under CA+ and PCA+ based plots indicate higher N availability under SSD fertigation. The increased N availability is primarily due to lower leaching losses with more frequent application (Wu et al., 2014; Lv et al., 2019), less volatilization losses due to sub-surface application (Lamm and Trooien, 2003; Engel et al., 2010; Zhang et al., 2019), and less denitrification due to higher ammonium (NH4 +) concentrations in the fertilized zone with localized application, inhibiting nitrifying bacteria and nitrification (Gao et al., 2019; Ning et al., 2019). Root morphological plasticity differ in heterogenous soil (Fengqin et al., 2018). Root proliferates when it encounters nutrient rich zone (Meng et al., 2012) to capture the nutrients effectively under CA+ and PCA+ . A frequent N application with 5 splits under SSD fertigated CA+ and PCA+ plots ensured crop's stage wise N requirement, whereas application of whole N dose in 3 split under CA and CT with flood irrigation failed to meet the stage specific N requirement. Also, the reduced root activity further decreased the N uptake under CT plots (Patel and Rajput, 2000; Zhou et al., 2017). The vegetative stage N remobilization to grain was observed higher in the SSD fertigated CA+ and PCA+ treatments, which was mainly due to higher N accumulation in plant biomass till flowering. Higher N accumulation in vegetative parts increases N remobilization to grain in the late reproductive stage (Nayak et al., 2022). According to Pan et al. (1986), a balanced contribution from reproductive stage N uptake and remobilized N from vegetative part contributes to a higher NUE. If crop N uptake is insufficient at the reproductive stage due to increased N demand, N remobilization is accelerated (Triboi and Triboi-Blondel, 2002). The higher crop growth and grain filling rate under CA+ and PCA+ plots increased the grain N demand, which in turn increased the remobilization of N to grains. We recorded comparatively lower stover N% in residue retained plots, which can be because of higher remobilization of N to grain under CA+ over PCA+ .

Nitrogen use efficiency (NUE) is an important indicator often used to describe how effectively crop utilizes the N to support growth and photosynthesis. We observed higher agronomic N use efficiency (AE_N) and apparent N recovery (AR_N) under CA+ and PCA+ practices, which further indicates higher N availability and lower N losses (Yolcu and Cetin, 2015; Jat et al., 2019). Contrarily, flooding or conventional furrow irrigation and broadcasting N fertilizer on the soil surface, resulted in significant nitrogen losses in CT and CA plots, lowering NUE (Liu et al., 2014). Further, the markedly higher maize grain yield and total N uptake under SSD fertigated CA+ and PCA+ plots compared to furrow irrigated CA and CT resulted in significantly higher AE_N and AR_N, respectively (Jat, and Sandhu et al., 2019, 2019).

4.3. Water use, water productivity, yield attributes and crop yield

Our study showed on average 54% irrigation water saving in maize under SSD irrigated CA+ and PCA+ compared to FI-CA and CT. This saving was mainly due to reduction /elimination of non-beneficial water components viz., evaporation, deep percolation and seepage and surface runoff (Irmak et al., 2016; Umair et al., 2019; Ajaz et al., 2020). Frequent water application at a lower rate, surface retention of crop residue, improvement of water stable aggregates, and improved soil physical and chemical properties are the causes that lead to improved crop growth and water productivity (Li et al., 2021; Patra et al., 2021a; Raina et al., 2013). Similar to our findings, Chen et al. (2015), Sandhu et al. (2019), and Jat et al. (2019) also reported reduction in irrigation water use and higher water productivity (WP) using SSD systems in cereal crops like maize, and wheat etc. The higher numerical WP value under CA+ versus PCA+ was due to crop residue retention, which may have contributed to soil moisture conservation by improving soil health, reducing evaporation loss, and thus lowering irrigation water requirement (Gathala et al., 2013; Irmak et al., 2016; Parihar et al., 2016a).

The SSD fertigated CA+ practice recorded highest stover and grain yield followed by PCA+ . The 27% and 30% increase in grain yield under CA+ over CA and CT, respectively was mainly the result of increased number of grains per cob and cob length. In previous study Patra et al. (2021b) reported a stronger correlation between cob length, grains per cob with grain yield in SSD fertigated CA+ and PCA+ plots than in conventionally fertilized, furrow irrigated CA and CT plots. The number of grains per cob increases as a result of proper grain filling, which in turn is linked to better availability of nitrogen and moisture, as well as reduced inter-plant competition (Wu et al., 2019). Inter-plant competition for water and nutrients may result in more barren grains per cob if water and nutrients become limiting (Sangoi, 2001). In CA and CT, irrigation at longer intervals resulted in higher degree of inter-plant competition for available soil moisture and N (Singandhupe et al., 2003), which may have increased the barren grains cob^{-1} and consequently decreased yield.

Improving distribution of LAI in cereal crops could be a desirable way to improve assimilation of photosynthates (Yin et al., 2000; Shiratsuchi et al., 2006; Jing et al., 2007). Our study showed enhanced LAI and PAR interception in drip fertigated CA+ and PCA+ plots over CA and CT. Our findings are consistent with those of Amanullah et al. (2010); Amanullah and Shah (2011), who observed an increase in mean leaf area, leaf area per plant and light interception, with increasing N rate and number of splits in maize. Further, a higher root density under SSDF (Martinez-Hernandez et al., 1991) led to greater uptake of moisture and nutrients, thereby enhancing the conversion of solar radiation into photosynthates. The improved grain and biomass yield under surface residue retention could also be explained by improved soil moisture and thermal regimes (Govaerts et al., 2007; Govaerts et al., 2009), better soil physical and biochemical properties (Verhulst et al., 2010; Parihar et al., 2016b; Parihar et al., 2018b), and improved nutrient availability and uptake (Nayak et al., 2022), etc.

4.4. Economics

The higher net return (NR) observed for subsurface drip fertigated CA+ and PCA+ treatments was attributed to a combination of factors, including increased crop yield, reduced costs of land preparation, seeding, fertilizer application and irrigation. The lower NR recorded under CA+ plots over PCA+ was due to cost associated with retaining 25% of the previous wheat residues in the field. In our study, the PCA+ and CA+ plots with 120 and 150 kg N ha^{-1} had a 21.7% and 40.6% higher NR, respectively, than the average NR of CA and CT plots with 120 kg N ha^{-1}. A number of researchers reported higher NR in SSD fertigated CA with or without residue retention, which is consistent with our findings. For example, Jat et al. (2019) reported that SSD in CA-based MWS provided 5.4% higher profitability over the conventional system (flood irrigation). Similarly, in a ZT based rice-wheat system Sidhu et al. (2019) reported 24.7% and 29.8% higher NR under CA+ (ZTRW + Residue + SSD) and PCA+ (ZTRW + No residue + SSD) system over flood irrigated conventional system (CTRW+ No Residue + Flooding). In addition, as in our case, here the COC was calculated after deducting an 80% GOI subsidy from the actual cost of a drip irrigation system.

5. Conclusions

The study aimed to assess complementarity of two novel technological interventions viz., CA and SSD on physiological behaviour, as well as crop yield, resource use efficiency and profitability of maize in water scarce IGP of NW India. The results indicated that the photosynthetic N use efficiency and water productivity were significantly improved at the key crop growth stages of maize under CA with SSD based plots (CA+, PCA+). The higher biomass and N accumulation till the end of vegetative stage provided a greater source strength for proper grain filling, leading to improved maize yield. Furthermore, CA with SSD-based treatments resulted in more dense and greener leaves from flowering to maturity, ensuring greater availability of photosynthates during the grain filling stage. This, coupled with vegetative stage-remobilized biomass and nitrogen, further enhanced maize yield. The retention of crop residue acted as an add-on to the benefits of SSD-based improved water and N management, helping to reduce unproductive N and moisture losses. Thus, our study presents compelling evidence of the benefits of implementing the CA + SSD technological intervention in maize cultivation, including water conservation, improving nitrogen-use efficiency, increased water productivity, and crop yield. These findings could serve as a strong backstop for popularization of CA+ technology in water scarce agroecology of IGP. Greater efforts should be directed toward raising farmers' awareness about the benefits of such promising technology for the cultivation of food grain as well as commercial crops like maize. Also, it is crucial to acknowledge that achieving these benefits requires significant expertise and knowledge in SSD usage, as well as a clear understanding of the associated costs and potential difficulties for farmers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

We sincerely acknowledge Indian Council of Agricultural Research (ICAR), ICAR-Indian Agricultural Research Institute (IARI), for providing the scholarship and other facilities. The research was conducted at CIMMYT-BISA Farm, Ludhiana, India funded by Indian Council of Agricultural Research (ICAR) under Window 3 grant to CIMMYT for Conservation Agriculture research. The support received from Divisions of Agronomy, Plant Physiology, Agricultural Physics, and Soil Science & Agricultural Chemistry of ICAR-IARI, New Delhi and ICAR-Indian Institute of Maize Research (IIMR) is also acknowledged. Special thanks to Dr. V.K. Singh, Former, Head, Division of Agronomy, ICAR-IARI, Dr. Raj Singh, Head (Acting), Division of Agronomy, ICAR-IARI, Dr. D.K. Singh, Professor, ICAR-IARI, Dr. P. Krishnan, Head, ICAR-IARI, Dr. Dr. V.K. Sharma, Pr. Scientist, ICAR-IARI, Dr. B.N. Mandal, Sr. Scientist, ICAR-IASRI, Dr. S. L. Jat, Scientist, ICAR-IIMR, Mr. Wassem Naguib, Asst. Researcher, Sugar Crops Research Institute, Egypt and Dr. Yadvinder-Singh, Dr. Naveen Gupta, Dr. K.M Choudhary, Mr. Sanjeev, Mr. Kashmiri of CIMMYT-BISA, and Mr. Sanjeev Kumar of ICAR-IIMR for assistance in data management and analysis work.

References

Ajaz, A., Datta, S., Stoodley, S., 2020. High plains aquifer–state of affairs of irrigated agriculture and role of irrigation in the sustainability paradigm. Sustainability 12, 3714.

Allison, J.C.S., Williams, H.T., Pammenter, N.W., 1997. Effect of specific leaf nitrogen content on photosynthesis of sugarcane. Ann. Appl. Biol. 31, 339–350.

Amanullah, Almas, L.K., Shah, P., 2010. Timing and rate of nitrogen application influence profitability of maize planted at low and high densities in Northwest Pakistan. Agron. J. 102, 575–579.

Amanullah, Shah, P., 2011. Nitrogen rates and its time of application influence dry matter partitioning and yield in maize planted at low and high densities. J. Plant Nutr. 34, 224–242.
Anand, A., Suresh, K., Nair, T.V.R., 2007. Photosynthetic variation and photosynthetic nitrogen-use efficiency in Brassica species with different genetic constitution of ribulose-1,5-bisphosphate carboxylase. Photosynthetica 45, 147–152.
Aryal, J.P., Sapkota, T.B., Jat, M.L., Bishnoi, K., 2015. On-farm economic and environmental impact of zero-tillage wheat: a case of north-west India. Exp. Agric. 51, 1–16.
Bhatt, R., Singh, P., Hossain, A., Timsina, J., 2021. Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy Water Environ. 19, 345–365.
Bouman, B.A.M., 2009. How much water does rice use? Rice Today 8, 28–29.
Bronson, K.F., Hunsaker, D.J., Meisinger, J.J., Rockholt, S.M., Thorp, K.R., Conley, M.M., Williams, C.F., Norton, E.R., Barnes, E.M., 2019. Improving nitrogen fertilizer use efficiency in subsurface drip-irrigated cotton in the desert southwest. Soil Sci. Soc. Am. J. 83, 1712–1721.
Çetin, O., Kara, A., 2019. Assesment of water productivity using different drip irrigation systems for cotton. Agric. Water Manag 223, 105693.
Chanh, T.T., Roeske, C.A., Eaglesham, A.R., 1993. Changes in maize-stalk proteins during ear development. Physiol. Plant. 87, 21–24.
Chen, R., Cheng, W., Liao, J., Fan, H., Zheng, Z., Ma, F., 2015. Lateral spacing in drip irrigated wheat: the effects on soil moisture, yield, and water use efficiencywater productivity. Field Crops Res 179, 52–62.
Choudhary, K.M., Jat, H.S., Nandal, D.P., Bishnoi, D.K., Sutaliya, J.M., Choudhary, M., Yadvinder-Singh, Sharma, P.C., Jat, M.L., 2018. Evaluating alternatives to rice-wheat system in western Indo-Gangetic plains: crop yields, water productivity and economic profitability. Field Crops Res 218, 1–10.
Chouhan, S.S., Awasthi, M.K., Nema, R.K., 2015. Studies on water productivity and yields responses of wheat based on drip irrigation systems in clay loam soil. Indian J. Sci. Tech. 8, 650–654.
Ciampitti, I.A., Vyn, T.J., 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res 121, 2–18.
Devkota, M., Martius, C., Lamers, J.P.A., Sayre, K.D., Devkota, K.P., Gupta, R.K., Egamberdiev, O., Vlek, P.L.G., 2013. Combining permanent beds and residue retention with nitrogen fertilization improves crop yields and water productivity in irrigated arid lands under cotton, wheat and maize. Field Crops Res 149, 105–114.
Eltarabily, M.G., Bali, K.M., Negm, A., Yoshimura, M.C., 2019. Evaluation of root water uptake and urea fertigation distribution under subsurface drip irrigation. Water 11 (7), 1487.
Engel, R., Liang, D.L., Wallander, R., Bembenek, A., 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. J. Environ. Qual. 39 (1), 115–125.
FAO, 2003. Methods of food analysis, in: FAO Food and nutrition paper 77: Food energy - methods of analysis and conversion factors. Report of a Technical Workshop, Rome, 3–6 December 2002, FAO, Rome, Italy. (Available at: ⟨https://www.fao.org/3/y5022e/y5022e03.htm#bm3)⟩.
Fengqin, H.U., Huoyan, W., Pu, M.O.U., Jianmin, Z., 2018. Nutrient composition and distance from point placement to the plant affect rice growth. Pedosphere 28, 124–134.
Gao, S., Hendratna, A., Cai, Z., Duan, Y., Qin, R., Tirado-Corbalá, R., 2019. Subsurface drip irrigation reduced nitrous oxide emissions in a pomegranate orchard. Intl. J. Environ. Sci. Dev. 10 (3), 79–85.
Gathala, M.K., Kumar, V., Sharma, P.C., Saharawat, Y.S., Jat, H.S., Singh, M., Kumar, A., Jat, M.L., Humphreys, E., Sharma, D.K., Sharma, S., Ladha, J.K., 2013. Optimizing intensive cereal-based cropping systems addressing current and future drivers of agricultural change in the northwestern Indo-Gangetic Plains of India. Agric. Ecosyst. Environ. 177, 85–97.
Gomez, K.A., Gomez, A.A., 1984. Statistical Procedures for Agricultural Research, second ed. John Wiley and Sons, New York. pp. 187.
Govaerts, B., Fuentes, M., Mezzalama, M., Nicol, J.M., Deckers, J., Etchevers, J.D., Figueroa-Sandoval, B., Sayre, K.D., 2007. Infiltration, soil moisture, root rot and nematode populations after 12 years of different tillage, residue and crop rotation managements. Soil . Res. 94, 209–219.
Govaerts, B., Sayre, K.D., Goudeseune, B., De Corte, P., Lichter, K., Dendooven, L., Deckers, J., 2009. Conservation agriculture as a sustainable option for the central Mexican highlands. Soil . Res. 103, 222–230.
Grassi, G., Magnani, F., 2005. Stomatal, mesophyll conductance and biochemical limitations to photosynthesis as affected by drought and leaf ontogeny in ash and oak trees. Plant Cell. Environ. 28, 834–849.
Guo, R., Sun, S., Liu, B., 2016. Difference in leaf water use efficiency water productivity/photosynthetic nitrogen use efficiency of Bt-cotton and its conventional peer. Sci. Rep. 6, 33539. https://doi.org/10.1038/srep33539.
Guo, S.Y., Zhang, X., Zhang, Q.J., Wang, Z.H., Li, Y.Z., Gu, S.F., Jiao, N.Y., Yin, F., Fu, G. Z., 2012. Effects of straw mulching and water-retaining agent on ear leaf senescence after anthesis and yield of summer maize. Maize Sci. 20, 104–107.
Gupta, N., Yadav, S., Humphreys, E., Kukal, S.S., Singh, B., Eberbach, P.L., 2016. Effects of tillage and mulch on the growth, yield and irrigation water productivity of a dry seeded rice-wheat cropping system in north-west India. Field Crops Res 196, 219–236.
Habbib, H., Hirel, B., Spicher, F., Dubois, F., Tétu, T., 2020. In winter wheat (*Triticum aestivum* L.), no- Improv. Photosynth. Nitrogen Water-Use Effic. J. Crop Sci. Biotechnol. 23, 39–46.
Humphreys, E., Kukal, S.S., Christen, E.W., Hira, G.S., Singh, B., Sudhir-Yadav, Sharma, R.K., 2010. Halting the groundwater decline in north-west India-which crop technologies will be winners. Adv. Agron. 109, 156–199.
Irmak, S., Djaman, K., Rudnick, D.R., 2016. Effect of full and limited irrigation amount and frequency on subsurface drip-irrigated maize evapotranspiration, yield, water productivitywater use efficiency and yield response factors. Irrig. Sci. 34, 271–286.
Irmak, S., Mohammed, A.T., Kukal, M.S., 2022. Maize response to coupled irrigation and nitrogen fertilization under center pivot, subsurface drip and surface (furrow) irrigation: growth, development and productivity. Agric. Water Manag. 263, 107457.
Jat, H.S., Sharma, P.C., Datta, A., Choudhary, M., Kakraliya, S.K., Yadvinder-Singh, Sidhu, H.S., Gerard, B., Jat, M.L., 2019. Re-designing irrigated intensive cereal systems through bundling precision agronomic innovations for transitioning towards agricultural sustainability in North-West India. Sci. Rep. 9, 17929.
Jat, M.L., Gathala, M.K., Saharawat, Y.S., Tetarwal, J.P., Gupta, R., Yadvinder-Singh, 2013. Double no-till and permanent raised beds in maize–wheat rotation of northwestern Indo- Gangetic plains of India: effects on crop yields, water productivity, profitability and soil. Field Crops Res 149, 291–299.
Jing, Q., Dai, T., Jiang, D., Zhu, Y., Cao, W., 2007. Spatial distribution of leaf area index and leaf N content in relation to grain yield and nitrogen uptake in rice. Plant Prod. Sci. 10 (1), 136–145.
Kumar, B.N.A., Azam-Ali, S.N., Snape, J.W., Weightman, R.M., Foulkes, M.J., 2011. Relationships between carbon isotope discrimination and grain yield in winter wheat under well-watered and drought conditions. J. Agric. Sci. 149, 257–272.
Lamm, F.R., Trooien, T.P., 2003. Subsurface drip irrigation for corn production: a review of 10 years of research in Kansas. Irrig. Sci. 22, 195–200.
Lemaire, G., Van Oosterom, E., Sheehy, J., Jeuffroy, M.H., Massignam, A., Rossato, L., 2007. Is crop N demand more closely related to dry matter accumulation or leaf area expansion during vegetative growth? Field Crops Res 100, 91–106.
Li, H., Mei, X., Wang, J., Huang, F., Hao, W., Li, B., 2021. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: a meta-analysis in China. Agric. Water Manag. 244, 106534.
Liu, Y., Li, Y.F., Li, J.S., 2014. Effects of nitrogen management on the growth and yield of mulched and drip-irrigated maize in northeast black soil. Reg. J. Hydraul. Eng. 45, 529–536.
Lv, H.F., Lin, S., Wang, Y.F., Lian, X.J., Zhao, Y.M., Li, Y.J., Du, J.Y., Wang, Z.X., Wang, J. G., Butterbach-Bahl, K., 2019. Drip fertigation significantly reduces nitrogen leaching in solar greenhouse vegetable production system. Environ. Pollut. 245, 694–701.
Majeed, A., Muhmood, A., Niaz, A., Javid, S., Ahmad, Z.A., Shah, S.S.H., Shah, A.H., 2015. Bed planting of wheat (*Triticum aestivum* L.) improves nitrogen use efficiency and grain yield compared to flat planting. Crop J. 3, 118–124.
Martinez-Hernandez, J.J., Bar-Yosef, B., Kafkafi, U., 1991. Effect of surface and subsurface drip fertigation on sweet corn rooting, uptake, dry matter production and yield. Irrig. Sci. 12, 153–159.
Meng, Q.F., Chen, X.P., Zhang, F.S., Cao, M.H., Cui, Z.L., Bai, J.S., Yue, S.C., Chen, S.Y., Müller, T., 2012. In-season root-zone nitrogen management strategies for improving nitrogen use efficiency in high-yielding maize production in China. Pedosphere 22, 294–303.
Merrill, A.L., Watt, B.K., 1973. Energy Value of Foods: Basis and Derivation. Agriculture Handbook No, 74. ARS United States Department of Agriculture, Washington DC.
Mutuku, E.A., Roobroeck, D., Vanlauwe, B., Boeckx, P., Cornelisa, W.M., 2020. Maize production under combined conservation agriculture and integrated soil fertility management in the sub-humid and semi-arid regions of Kenya. Field Crops Res 254, 107833.
Nayak, H.S., Parihar, C.M., Mandal, B.N., Patra, K., Jat, S.L., Singh, R., Singh, V.K., Jat, M.L., Garnaik, S., Nayak, J., Abdallah, A.M., 2022. Point placement of late vegetative stage nitrogen splits increase the productivity, N-use efficiency and profitability of tropical maize under decade long conservation agriculture. Eur. J. Agron. 133, 126417.
Ning, D.F., Qin, A.Z., Duan, A.W., Xiao, J.F., Zhang, J.Y., Liu, Z.J., Liu, Z.G., zhao, B., Liu, Z.D., 2019. Deficit irrigation combined with reduced N-fertilizer rate can mitigate the high nitrous oxide emissions from Chinese drip-fertigated maize field. Glob. Ecol. Conserv. 20, e00803.
Nobel, P.S., 1980. Interception of photosynthetically active radiation by cacti of different morphology. Oecologia 45, 160–166.
Pan, W.L., Camberato, J.J., Jackson, W.A., Moll, R.H., 1986. Utilization of previously accumulated and concurrently absorbed nitrogen during reproductive growth in maize. Plant Physiol. 82, 247–253.
Pandey, R., Paul, V., Singh, M.P., 2017. Measurement of photosynthesis using infrared gas analyzer. Man. ICAR Spons. Train. Program. –Physiological Tech. Anal. Impact Clim. Change Crop Plants Div. Plant Physiology, IARI, N. Delhi 19–22.
Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pradhan, S., Chakraborty, D., Jat, M.L., Jat, R.K., Saharawat, Y.S., Yadav, O.P., 2016a. Long term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic plains. Soil . Res. 161, 116–128.
Parihar, C.M., Jat, S.L., Singh, A.K., Kumar, B., Yadvinder-Singh, Pradhan, S., Pooniya, V., Dhauja, A., Chaudhary, V., Jat, M.L., Jat, R.K., Yadav, O.P., 2016b. Conservation agriculture in irrigated intensive maize -based systems of north-western India: effects on crop yields, water productivity and economic profitability. Field Crops Res 193, 104–116.
Parihar, C.M., Yadav, M.R., Jat, S.L., Singh, A.K., Kumar, B., Pooniya, V., Pradhan, S., Verma, R.K., Jat, M.L., Jat, R.K., Parihar, M.D., Nayak, H.S., Saharawat, Y.S., 2018a. Long-term conservation agriculture and intensified cropping systems: effects on

growth, yield, water, and energy-use efficiency of maize in Northwestern India. Pedosphere 28, 952–963.
Parihar, C.M., Jat, S.L., Singh, A.K., Datta, A., Parihar, M.D., Varghese, E., Bandyopadhyay, K.K., Nayak, H.S., Kuri, B.R., Jat, M.L., 2018b. Changes in carbon pools and biological activities of a sandy loam soil under medium-term conservation agriculture and diversified cropping systems. Eur. J. Soil Sci. 69, 902–912.
Patel, N., Rajput, T.B.S., 2000. Effect of fertigation on growth and yield of onion. In: Singh, H.P., Kaushish, S.P., Kumar, A., Murthy, T.S., Samuel, J.C. (Eds.), Micro Irrigation. Central Board of Irrigation and Power Publication 282. Central Board of Irrigation and Power Publications, New Delhi, pp. 451–454.
Patra, K., Parihar, C.M., Nayak, H.S., Rana, B., Singh, V.K., Jat, S.L., Panwar, S., Parihar, M.D., Singh, L.K., Sidhu, H.S., Jat, Gerard, B., Jat, M.L., 2021a. Water budgeting in conservation agriculture-based sub-surface drip irrigation in tropical maize using HYDRUS-2D. Sci. Rep. 11, 16770.
Patra, K., Parihar, C.M., Nayak, H.S., Rana, B., Singh, V.K., Krishnan, P., Pandey, R., Mandal, B.N., Rathi, N., Meena, B.R., Singh, L.K., Sidhu, H.S., Jat, M.L., 2021b. Crop performance and nitrogen use efficiency in maize under conservation agriculture coupled with sub-surface drip fertigation. Indian J. Agric. Sci. 91 (3), 472–479.
Pereira, L.S., Cordery, I., Iacovides, I., 2012. Improved indicators of water use performance and productivity for sustainable water conservation and saving. Agric. Water Manag. 108, 39–41.
Poorter, H., Evans, J.R., 1998. Photosynthetic nitrogen-use efficiency of species that differ inherently in specific leaf area. Oecologia 116, 26–37.
Qiang, S., Zhang, F., Dyck, M., Zhang, Y., Xiang, Y., Fan, J., 2019. Determination of critical nitrogen dilution curve based on leaf area index for winter wheat in the Guanzhong Plain. Northwest China J. Integr. Agric. 18 (10), 2369–2380.
Qin, S., Li, S., Kang, S., Du, T., Tong, L., Ding, R., 2016. Can the drip irrigation under film mulch reduce crop evapotranspiration and save water under the sufficient irrigation condition? Agric. Water Manag. 177, 128–137.
Rai, V., Pramanik, P., Das, T.K., Aggarwal, P., Bhattacharyya, R., Krishnan, P., Sehgal, V. K., 2019. Modelling soil hydrothermal regimes in pigeon pea under conservation agriculture using Hydrus-2D. Soil . Res. 190, 92–108.
Raina, J.N., Suman, S., Kumar, P., Spehia, R.S., 2013. Effect of drip fertigation with and without mulch on soil hydrothermal regimes, growth, yield, and quality of apple (*Malus domestica* Borkh). Commun. Soil Sci. Plan 44, 2560–2570.
Ripley, B.S., Gilbert, M.E., Ibrahim, D.G., Osborne, C.P., 2007. Drought constraints on C4 photosynthesis: stomatal and metabolic limitations in C3 and C4 subspecies of *Alloteropsis semialata*. J. Exp. Bot. 58, 1351–1363.
Sampathkumar, T., Pandian, B.J., 2012. Effect of fertigation frequencies and levels on growth and yield of maize. Madras Agric. J. 97 (7–9), 245–248.
Sandhu, O.S., Gupta, R.K., Thind, H.S., Jat, M.L., Sidhu, H.S., Yadvinder-Singh, 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. Agric. Water Manag. 219, 19–26.
Sangoi, L., 2001. Understanding plant density effects on maize growth and development: an important issue to maximize grain yield. Ciência Rural 31 (1), 159–168.
Sharma, P.C., Jat, H.S., Kumar, V., Gathala, M.K., Datta, A., Yaduvanshi, N.P.S., Choudhary, M., Sharma, S., Singh, L.K., Saharawat, Y., Yadav, A.K., Parwal, A., Sharma, D.K., Singh, G., Jat, M.L., Ladha, J.K., McDonald, A., 2015. Sustainable intensification opportunities under current and future cereal systems of North-West India. technical bulletin: CSSRI/Karnal/2015/4. ICAR-central soil salinity research institute, Karnal, Haryana. India 46.
Shen, D., Zhang, G., Xie, R., Ming, B., Hou, P., Xue, J., Li, S., Wang, K., 2020. Improvement in photosynthetic rate and grain yield in super-high-yield maize (*Zea mays* L.) by optimizing irrigation interval under mulch drip irrigation. Agronomy 10, 1778.
Shiratsuchi, H., Yamagishi, T., Ishii, R., 2006. Leaf nitrogen distribution to maximize the canopy photosynthesis in rice. Field Crops Res 95, 291–304.
Sidhu, H.S., Jat, M.L., Yadvinder-Singh, Sidhu, R.K., Gupta, N., Singh, P., Jat, H.S., Gerard, B., 2019. Sub-surface drip fertigation with conservation agriculture in a rice-wheat system: a breakthrough for addressing water and nitrogen use efficiency. Agric. Water Manag. 216, 273–283.
Singandhupe, R.B., Rao, G.G.S.N., Patil, N.G., Brahmanand, P.S., 2003. Fertigation studies and irrigation scheduling in drip irrigation system in tomato crop (*Lycopersicon esculentum* L.). Eur. J. Agron. 19, 327–340.
Triboi, E., Triboi-Blondel, A.M., 2002. Productivity and grain or seed composition: a new approach to an old problem. Eur. J. Agron. 16, 163–186.
Umair, M., Hussain, T., Jiang, H., Ahmad, A., Yao, J., Qi, Y., Zhang, Y., Min, L., Shen, Y., 2019. Water-saving potential of subsurface drip irrigation for winter wheat. Sustainability 11, 2978.
Verhulst, N., Govaerts, B., Verachtert, E., Castellanos-Navarrete, A., Mezzalama, M., Wall, P.C., Chocobar, A., Deckers, J., Sayre, K.D., 2010. Conservation agriculture, improving soil quality for sustainable production system? In: Lal, R., Stewart, B.A. (Eds.), Advances in Soil Science: Food Security and Soil Quality. CRC Press, Boca Raton, FL, USA.
Wan, X.J., Wu, W., Liao, Y.S., 2021. Mitigating ammonia volatilization and increasing nitrogen use efficiency through appropriate nitrogen management under supplemental irrigation and rain-fed condition in winter wheat. Agric. Water Manag. 255, 107050.
Wu, D.L., Xu, X.X., Chen, Y.L., Shao, H., Sokolowski, E., Mi, G.H., 2019. Effect of different drip fertigation methods on maize yield, nutrient and water productivity in two-soils in Northeast China. Agric. Water Manag. 213, 200–211.
Wu, J., Guo, W., Feng, J., Li, L., Yang, H., Wang, X., Bian, X., 2014. Greenhouse gas emissions from cotton field under different irrigation methods and fertilization regimes in arid north western China. Sci. World J. 2014, 407832.
Yadvinder-Singh, Kukal, S.S., Jat, M.L., Sidhu, H.S., 2014. Improving water productivity of wheat-based cropping systems in South Asia for sustained productivity. Adv. Agron. 127, 157–258.
Yin, X., Schapendonk, A.D.H.C.M., Kropff, M.J., Van Oijen, M., Bindraban, P.S., 2000. A generic equation for nitrogen limited leaf area index and its application in crop growth models for predicting leaf senescence. Ann. Bot. 85, 579–585.
Yolcu, R., Cetin, O., 2015. Nitrogen fertigation to improve nitrogen use efficiency and crude protein on silage corn. Turk. J. Field Crop 20, 233–241.
Zhang, X., Meng, F.Q., Li, H., Wang, L.G., Wu, S.X., Xiao, G.M., Wu, W.L., 2019. Optimized fertigation maintains high yield and mitigates N_2O and NO emissions in an intensified wheat–maize cropping system. Agric. Water Manag. 211, 26–36.
Zhou, B.Y., Sun, X.F., Ding, Z.S., Ma, W., Zhao, M., 2017. Multi-split nitrogen application via drip irrigation improves maize grain yield and nitrogen use efficiency. Crop Sci. 57, 1687–1703.