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SUB-SURFACE DRIP FERTIGATION ENHANCES SEED COTTON YIELD AND ECONOMIC RETURNS IN SEMI-ARID ENVIRONMENTS

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ABSTRACT

Surface flood (SF) method to irrigate cotton in India results in huge wastage and necessitates adopting efficient water management strategies. Therefore, a field experiment was conducted during 2019 at 2 different agro-climatic locations (Faridkot and Abohar) to investigate the effect of sub-surface drip fertigation (SSDF) on seed cotton yield (SCY), and productivity indices in comparison with SF and surface-drip fertigation (SDF). The field experiment had 8 treatments arranged in a complete randomized block design, wherein 3 levels of sub-surface drip irrigation-SSDI (i.e. 0.6, 0.8 and 1.0 ETc-crop evapotranspiration) and 2 nitrogen levels [75% RDN (recommended dose of nitrogen) and 100% RDN (112.5 kg N ha^{-1})] were applied in 6 combinations, while SF (Control 1) and SDF of 0.8 ETc (Control 2), both with 100% RDN served as controls. SSDI levels of 0.8 and 1.0 ETc showed 27% and 29% better SCY as compared to SF (2626 kg ha^{-1}). Quantity of applied water under SF was 56% and 110% higher as compared to highest level SSDI of 1.0 ETc, for Faridkot and Abohar, respectively. A SSDF of 0.8ETc along with 100% RDN recorded improved SCY by 33% besides higher NUE by 24% over SF. Net returns under SF remained lesser by 35% and 37% compared to SSDI of 0.8 ETc and SSDI of 1.0 ETc, respectively. These findings clearly elucidated the advantage of SSDF applied at 0.8 ETc along with 100% RDN in enhancing cotton yield and monetary benefits as compared to surface flood.

Keywords: Bio-physical water productivity, Cotton, Drip fertigation, Economic water productivity, Nitrogen use efficiency, Seed cotton yield

Cotton (*Gossypium hirsutum* L.) is one among the most important cash crops being grown in India and sustains nation's largest organized textile industry. In Punjab, cotton is mainly grown in the south-western districts which are characterized by light textured soils, brackish underground water and arid climate with limited canal water as a prime source of irrigation (Singh *et al.,* 2018). Here cotton crop is traditionally irrigated through surface flood (SF) method at 4-6 growth stages with approximately 100-150 mm of water for single irrigation. Average rainfall in cotton growing zones of Punjab varies from 200-400 mm, which leads to water stress at certain growth stages, whereas few stages experience excess of water during monsoon. Fresh water availability in near future would be drastically reduced for agrarian purposes besides being severely affected by traditional practices like SF method of irrigation. This necessitates for adoption of improved and efficient water application strategies to increase the crop productivity with better irrigation management as faulty irrigation approaches in cotton are wasting scarce fresh water available besides sub-optimal yield levels (Singh *et al.,* 2020). Nevertheless, productivity of cotton in Punjab also suffers from poor irrigation water availability and its defective scheduling. Poor distribution of rainfall and large scale cultivation of rice in this region compel the farmers to pump the ground water leading to depletion of water resources of Punjab at a very alarming rate of 0.4-0.9 m year^{-1} (Brar *et al.,* 2012). Therefore, precise and efficient usage of water resources has been a vital need to achieve better production with every drop of water used. Hence, efficient water management strategies must be incorporated in order to increase the water productivity so that a balance between water consumption and yield obtained could be maintained. Moreover, precise and limited irrigation supply needs to be evaluated for replacement of full and faulty irrigation application so as to check the depletion of limited water resources globally. Wasteful system of flood irrigation should be exchanged with more efficient irrigation systems to conserve water. Different irrigation systems such as drip irrigation (DI), sub-surface drip irrigation (SSDI) and sprinkler irrigation were found to improve irrigation efficiency (Ines *et al.,* 2006). Drip fertigation is an efficient system which saves both water and nutrients as they are applied directly to the root zone of plants without compromising productivity levels. It is an important water management technique that exposes crop to a certain level of water stress during crop growth stages without any significant reduction in the crop yield (Pereira et al. 2012), besides improving the water use efficiency and uptake of nutrients (Kaur and Brar, 2016).

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Nowadays, sub-surface drip irrigation (SSDI) is also gaining importance due to more efficient usage of water since there is minimum surface runoff and evaporation from soil surface as laterals having drippers are buried under the soil surface at a regular spacing (Mchugh *et al.,* 2008). SSDI can play a greater role in water management throughout arid and semi-arid regions by applying water and nutrients more precisely to the field in both position and quantity. SSDI has resulted in 20% water saving in organic olive over conventional method (Martinez and Reca, 2014) and 10% higher water use efficiency (WUE) over surface drip irrigation (SDI) in cotton (Roopashree *et al.,* 2016). SSDI reduces evaporation from the soil surface in comparison to SDI and SF because water is delivered directly to the roots as laterals are located within the root zone, thus minimizing water loss (Neelakanth *et al.,* 2019). Application of fertilizers with irrigation water also known as fertigation can be used as an effective tool to curb the nutrient losses occurring globally due to faulty application as they are applied in proximity of plant roots (Bar-yosef, 1999). Fertigation system leads to lesser loss of nutrients by leaching and volatilization, thereby increasing the availability of nutrient to plants (Singh *et al.,* 2018).

Therefore, fertigation system can be explored as a potential tool to reduce the water and nutrient losses with enhanced yield in north-western India. So far feasibility of SSDI in cotton agro-ecosystems has never been evaluated before in north-western India and till date little research work has been documented on SSDF in cotton. Hence, present study was initiated to optimize the SSDF for increasing the yield and water productivity so as to achieve potential yield with additional saving of water and N fertilizer.

MATERIALS AND METHODS

Location and weather

A field trial was conducted at Regional Research Stations (RRS) of Punjab Agricultural University located at Faridkot and Abohar during *summer* season (April-November) of 2019. These Research Stations are located 96 km apart in two distinct agro-climatic locations of south-western cotton belt of Punjab state. Experimental site of RRS, Faridkot lies in Agro climatic zone-IV at an altitude of 211 m above mean sea level (AMSL) and a latitude of 30º 40’ N and longitude of 74º 44’ E whereas, experimental site of RRS, Abohar lies in Agro climatic zone-V at an altitude of 186 m AMSL and a latitude of 30º 08’ N and longitude of 74º 12’ E. Both of experimental locations fall in the Trans Gangetic plain zone of India with climate characterized by sub-tropical and semi-arid conditions experiencing dry and hot summer from mid-April to June and cold winter season from November to January, and truly represent the cotton belt of north-western region of India. Soil characteristics of the experimental sites are given in Table 1. The average annual rainfall of both the sites varies from 200-400 mm with 75% of total precipitation mainly occurring from July-September as summer monsoon.

Experimental details

The experiment having 8 treatments was laid out in a complete randomized block design with three replication. It comprised of six treatment combinations from three levels of SSDI (0.6 ETc, 0.8 ETc and 1.0 ETc of PAN evapotranspiration) and two N fertigation levels [75% RDN (84.4 kg N ha^{-1}) and 100% RDN (112.5 kg N ha^{-1})]. In addition, there were two extra control treatments i.e. SF method of irrigation (Control 1) and SDI at 0.8 ETc along with 112.5 kg N ha^{-1}(Control 2). Various treatment combinations included T_1: SSDI at 0.6 ETc with DF of 75% RDN; T_2: SSDI at 0.6 ETc with DF of 100% RDN; T_3:SSDI at 0.8 ETc with DF of 75% RDN; T_4: SSDI at 0.8 ETc with DF of 100% RDN; T_5: SSDI at 1.0 ETc with DF of 75% RDN; T_6: SSDI at 1.0 ETc with DF of 100% RDN; T_7: SF irrigation with 100 % RDN through broadcasting of urea-Control 1 and T_8: SDI at 0.8 ETc with DF of 100 % RDN-Control 2.Level of P and K was similar across all treatments.

Methodology and crop management

After harvesting of wheat crop, the field was ploughed twice and pre-sowing irrigation (*rauni*) was

Table 1. Soil characteristics of the experimental sites

Soil property	Abohar	Faridkot
Soil texture	Sandy Loam	Loamy
pH	8.32	8.3
Organic carbon (%)	0.42	0.51
Available nitrogen (kg ha^{-1})	192	188
Electrical conductivity (dS m^{-1})	0.18	0.16
Available phosphorus (kg ha^{-1})	35.0	21.2
Available potash (kg ha^{-1})	530	638

applied at both study locations. *Bt* cotton hybrid cultivar (RCH773 BGII) was sown on May 9, 2019 and May 23, 2019 at Faridkot and Abohar, respectively. The seed sowing was done manually by hand dibbling method using 2 seeds hill^{-1} at uniform depth of approximately 5 cm throughout the experimental field. Uniform inter row spacing of 67.5 cm and intra row spacing of 75 cm within plants was kept as per university recommendations. Each experimental plot (60.75 m^2) had 125 plants arranged in 5 rows, while each row length was 18 m. Sub-surface laterals for SSDI were installed using a tractor operated machine at an uniform depth of 30 cm having row to row spacing of 67.5 cm with emitter discharge rate of 2.2 lh^{-1} in laterals placed at 75 cm. However, for Control 2, SDI drip laterals with similar discharge were manually laid out on ground surface. The control 1 plots receiving irrigation through SF were delivered water through dedicated PVC pipes.

Growth, yield attributing characters and seed cotton yield

Growth and yield attributing parameters like plant height, sympodial branches plant^{-1}, bolls plant^{-1} and boll weight were recorded from ten randomly selected plants per plot. Biomass accumulation was measured by cutting whole above ground portion of the plant after harvest and then weighed after thorough drying under the sun. SCY constituted total weight of both the hand

Table 2. Effect of various treatments on growth parameters, yield attributes and seed cotton yield (Pooled means).

	Irrigation regimes (IR)					
Nitrogen fertigation schedules (FS)	0.6 ETc	0.8 ETc	1.0 ETc	Mean	Surface flood (Control 1)	Surface drip (Control 2)
Plant height (cm)						
75% RDN	129.0	153.0	153.3	145.1		
100% RDN	133.5	155.0	154.5	147.6		
Mean	131.2	154.0	153.8		142.2	160.9
LSD (p=0.05)	IR = 8.2; FS = NS; IR*FS = NS; IR*FS vs. Controls =6.1					
Sympodial branches plant^{-1}						
75% RDN	14.6	18.9	19.6	17.7		
100% RDN	16.3	20.5	21.7	19.5		
Mean	15.4	19.7	20.6		19.0	21.7
LSD (p=0.05)	IR = 1.3; FS =1.1; IR*FS =NS; IR*FS vs. Controls =1.0					
Bolls plant^{-1}						
75% RDN	44.0	57.5	60.0	53.8		
100% RDN	48.3	63.1	64.7	58.7		
Mean	46.2	60.3	62.3		44.3	60.0
LSD (p=0.05)	IR = 2.5; FS = 2.1; IR*FS = NS; IR*FS vs. Controls = 2.3					
Boll weight (g)						
75% RDN	3.56	3.99	4.06	3.87		
100% RDN	3.69	4.02	4.07	3.93		
Mean	3.63	4.00	4.06		3.97	4.24
LSD (p=0.05)	IR =0.12; FS =NS; IR*FS = NS; IR*FS vs. Controls =0.10					
Seed cotton yield (kg ha^{-1})						
75% RDN	2501	3202	3221	2975		
100% RDN	2816	3484	3550	3283		
Mean	2658	3343	3385		2626	3298
LSD (p=0.05)	IR =151; FS = 123; IR*FS = NS; IR*FS vs. Controls = 127					
Biomass accumulation (g m^{-2})						
75% RDN	1863.3	2388.0	2663.5	2304.9		
100% RDN	2123.6	2518.1	2716.4	2452.7		
Mean	1993.5	2453.0	2689.9		2108.0	2440.6
LSD (p=0.05)	IR = 50.7; FS = 41.1; IR*FS =NS; IR*FS vs. Controls =39.0					

* Where RDN: recommended dose of nitrogen; NS: non-significant; LSD: least significant difference.
Control 1: Surface flood irrigation and soil application of 100 % RDN;
Control 2: Surface drip irrigation @0.8 ETc with fertigation of 100 % RDN

pickings and is expressed in kg ha^{-1}.

Irrigation, fertilizer application and productivity indices

Irrigation under the SDI and SSDI method was applied at an interval of every 5 days and the amount of irrigation water varied according to treatments, which were based on amount of crop evapo-transpiration except for the conventional SF method, where water was applied by flood irrigation. The soil moisture content (%) was measured by gravimetric method before irrigation in various plots. Soil samples from 2 locations at random in each plot were combined to make a composite sample for soil moisture determination. Then, irrigation was applied to designated plots as per protocol. Surface run-off was nil as sufficient buffers were maintained. Deep drainage was considered zero, when the moisture storage in soil profile was less than the field capacity and when soil moisture storage exceeded the field capacity storage after irrigation or rain. Thereafter, deep drainage was calculated as the difference between field capacity storage and soil moisture storage plus rainfall/ irrigation. The quantity of each irrigation was measured by using water meter in all the treatment plots and water applied under each irrigation was summed up to calculate total irrigation water. To work out ETc, evapotranspiration was measured using reference evapotranspiration calculator developed by FAO using site specific weather data. According to user manual by FAO, value of crop coefficients (K_c) of cotton crop was 0.75 till end June, 1.15 during July and August and 0.70 till the picking of cotton to calculate the daily crop evapotranspiration (ETc). Fertilizer N in form of urea was applied for SDF and SSDF treatments starting from 35 days after sowing and delivered in ten equal splits after every 5 days except for the SF, where 100% RDN was applied in two equal splits, i.e. half dose at thinning and remaining half dose at flowering. Application of phosphorous was skipped as recommended dose of P was applied to previous season wheat crop as per recommendations of Punjab Agricultural University (Anonymous, 2022). Actual crop evapotranspiration (ET_a) was worked out with the help of soil water balance equation (Fernandez *et al.,* 2020). Bio-physical water productivity (BWP), and economic water productivity (EWP) was computed by using following equations (FernÃ¡ndez et al., 2020; Singh et al.,2022).

$$\text{BWP (kg m}^{-3}\text{)} = SCY/ET_a \qquad (1)$$

$$\text{EWP (\$ m}^{-3}\text{)} = NR/ET_a \qquad (2)$$

Where, SCY means seed cotton yield in kg ha^{-1}, ET_a is actual crop evapotranspiration (m^3 ha^{-1}) and NR indicates net returns in \$ ha^{-1}.

Water use efficiency (WUE) was calculated by using the following equations.

$$WUE = ET_a / IW+R\pm\Delta S \qquad (3)$$

Where, IW is irrigation water applied (m^3 ha^{-1}), and R represents rainfall (m^3 ha^{-1}), ± ΔS change in soil profile moisture (m^3 ha^{-1}), while ETa indicates actual crop evapotranspiration (m^3 ha^{-1}).

Nitrogen use efficiency (NUE) is calculated using under given formula

$$\text{NUE= Seed cotton yield /N applied} \qquad (4)$$

Fibre quality parameters

Lint samples were obtained by ginning the clean and dried weighed sample of seed cotton through single roller electric gin and ginning outturn (GOT) of the cotton was computed by using following formula.

Ginning out turn (%) = (weight of lint in grams / weight of seed cotton in grams) x 100

Other fibre quality parameters were calculated as described by Singh et al (2022).

Economics

Total cost of cultivation incurred for raising cotton crop was calculated with the help of Enterprise budget (2020) of *Kharif* crops by Department of Economics and Sociology, PAU, Ludhiana. B: C was also worked to check the economic feasibility of treatments and is worked out by dividing net returns by the total cost of cultivation (Singh *et al.,* 2020).

Statistical analysis

Statistical analysis of various recorded and calculated parameters was performed to evaluate the effect of various SSDI regimes and N fertigation levels and their comparison with control treatments by using Statistical package, CPCS-I software developed by the Department of Mathematics and Statistics, PAU, Ludhiana (Punjab).

RESULTS AND DISCUSSION

Growth parameters and biomass accumulation

Different irrigation and fertigation treatments exerted significant effect on growth parameters like plant height and biomass accumulation (Table 2). Among tested irrigation regimes (IR), taller plants were recorded under SDI (160.9 cm), closely followed by SSDI level of 0.8 ETc (154.0 cm) and 1.0 ETc (153.8 cm), while significant reduction in plant height was observed under 0.6 ETc (131.2 cm) and SF (142.2 cm). Biomass accumulation was highest under a SSDI level of 1.0 ETc (2689.9 g m^{-2}) as compared to 0.8 ETc (2453.0 g m^{-2}) and 0.6 ETc (1993.5 g m^{-2}). However, both SDI and SSDI at 0.8 ETc remained on par for biomass accumulation. Contrarily, significant reduction by 22% and 14% was revealed for biomass under SF (2108.0 g m^{-2}) over SSDI levels of 1.0 ETc and 0.8 ETc, respectively. Reduced plant height and biomass accumulation under SSDI level of 0.6 ETc might be due to the fact that here least water supply (251.2 mm) was available to plants, which in turn failed to maintain optimal crop growth. Better plant vigour under SDI over SF in present findings is in close proximity with Yadav and Chauhan (2016), who observed taller plants by 9% under DI over SF. Furthermore, SF not only recorded shorter plants in line with Prajapati and Subbaiah (2018), but also lesser biomass accumulation in comparison to various SDF/SSDF treatments under 0.8/1.0 ETc, revealing that applied water and nitrogen could not be efficiently utilized under SF and thus failed to maintain optimal crop growth.

Among N fertigation schedules, plant height varied non-significantly. Nevertheless, both SSDF levels of 75% RDN and 100% RDN revealed better plant height and biomass accumulation over the SF method, owing to the optimum availability of water and nitrogen in accordance with Ayyadurai and Manickasundaram (2014). However, maximum increase in plant height and biomass accumulation was recorded when SSDI increased from 0.6 ETc to 0.8 ETc, whereas only marginal increase was observed while moving from 0.8 ETc to 1.0 ETc. These findings could establish that water and nitrogen to be essential growth factors as evident from better height and biomass accumulation under their increased supply, thus showing a linear relation between resources and growth parameters (Table 2). Higher biomass accumulation under SSDI over SF method is fairly supported by Sampthkumar *et al.* (2006) who recorded higher biomass accumulation (4625 g m^{-2}) under DI over border strip (2490 g m^{-2}) and SF (2322 g m^{-2}) methods of irrigation. Present study clearly signifies that SSDI of 0.8 ETc or 1.0 ETc could be utilized for maintaining the optimum moisture condition in the soil profile under test environments.

Yield attributes and seed cotton yield

Sympodial branches (reproductive branches), bolls plant^{-1}, boll weight and SCY varied significantly under various irrigation regimes (Table 2). Higher sympodial branches plant^{-1} were recorded under SDI (21.7) closely followed by SSDI of 1.0 ETc (20.6), 0.8 ETc (19.7) and SF method (19.0), while value was least under SSDI of 0.6 ETc (15.4). Improved sympodial branches plant^{-1} under SSDI is in conformity with Ali *et al.* (2017) who reported 15% higher sympodial branches plant^{-1} under SDI over furrow method. Significantly higher bolls plant^{-1} was revealed under SSDI of 1.0 ETc (62.3) and 0.8 ETc (60.3) over SSDI of 0.6 ETc (46.2) and SF method (44.3) in line with Prajapati and Subbaiah (2018) who recorded more bolls plant^{-1} under SDI at 1.0 ETc over furrow method. A significant reduction by 27% and 29% for bolls plant^{-1} under SF method over SSDI of 0.8 ETc and 1.0 ETc was evident. Data further revealed that though bolls plant^{-1} continued to increase with enhanced quantum of applied water but significant improvement could be observed only upto 0.8 ETc with a non-significant increase at 1.0 ETc. Higher boll weight was recorded under SDI (4.24 g) closely followed by SSDI at

Table 3. Irrigation water applied and actual crop evapotranspiration under various treatments.

Treatment	Faridkot						Abohar					
	IWA (mm)	RF (mm)	Δ S (mm)	ET_a (mm)	D (mm)	R. (mm)	IWA (mm)	RF (mm)	Δ S (mm)	ET_a (mm)	D (mm)	R. (mm)
T_1: SSDI@ 0.6 ETc with DF of 75% RDN	251.2	366.1	-21.0	504.6	94.3	39.4	154.3	353.3	-18.2	380.1	89.6	56.1
T_2: SSDI@ 0.6 ETc with DF of 100% RDN	251.2	366.1	-19.4	530.2	72.5	34.0	154.3	353.3	-16.5	385.6	92.3	46.2
T_3: SSDI@ 0.8 ETc with DF of 75% RDN	301.6	366.1	-17.2	553.9	99.0	32.0	172.3	353.3	-12.8	404.6	98.2	35.6
T_4: SSDI@ 0.8 ETc with DF of 100% RDN	301.6	366.1	-18.1	576.8	74.6	34.4	172.3	353.3	-10.1	451.1	69.2	15.4
T_5: SSDI@ 1.0 ETc with DF of 75% RDN	352.0	366.1	-10.9	554.6	139.3	35.1	190.4	353.3	-4.8	403.7	99.2	45.6
T_6: SSDI@ 1.0 ETc with DF of 100% RDN	352.0	366.1	-8.5	580.6	109.4	36.4	190.4	353.3	-2.1	462.8	70.4	12.6
T_7:Surface flood with 100% RDN (Control 1)	550.0	366.1	45.0	485.6	299.1	86.4	400.0	353.3	32.8	345.8	281.4	93.3
T_8:Surface drip @0.8 ETc with 100% RDN (Control 2)	301.6	366.1	-6.7	555.2	73.9	45.3	172.3	353.3	-4.3	410.8	80.2	38.9

* Where IWA: irrigation water applied; RF: rainfall; **ΔS: change in soil profile moisture;** ET_a: actual crop evapotranspiration; D: Drainage; R.: Runoff

1.0 ETc (4.06 g) and 0.8 ETc (4.00 g), while SSDI at 0.6 ETc recorded significantly lowest (3.63 g) primarily due to reduced water supply. Among SSDI levels, SCY was maximum at 1.0 ETc (3385 kg ha^{-1}) closely followed by 0.8 ETc (3343 kg ha^{-1}), while least under 0.6 ETc (2658 kg ha^{-1}), where it was 20% and 21% lower as compared to 0.8 ETc and 1.0 ETc, respectively. Nevertheless, SDI recorded statistically at par SCY with SSDI of 0.8 ETc (3343 kg ha^{-1}) and 1.0 ETc. However, SSDI of 0.8 ETc and 1.0 ETc recorded 27% and 29% higher SCY over SF (2108 kg ha^{-1}) due to better yield parameters in line with Aladakatti *et al.* (2012) who observed at par yield at SDI of 1.0 ETc (2791 kg ha^{-1}) and 0.8 ETc (2697 kg ha^{-1}), but a significantly lower yield at 0.6 ETc (2536 kg ha^{-1}) and SF of irrigation (2648 kg ha^{-1}) in southern India. The bolls $plant^{-1}$ was 36% and 40.6 % higher under SSDI level of 0.8 ETc and 1.0 ETc over SF method, while they were 31% and 35% higher respectively, over 0.6 ETc. Singh *et al.* (2018) also reported significantly higher SCY by 19% and 23% over the traditional SF method under SDI of 1.0 ETc and 0.8 ETc, which endorses present findings. Improved SCY and yield attributes such as higher bolls $plant^{-1}$ under SSDI of 1.0 ETc and 0.8 ETc over SF irrigation in current findings is in accordance with Neelakanth *et al.* (2019) who reported 12% higher yield under SSDI over SF method.

Various fertigation levels also exerted significant effect on sympodial branches $plant^{-1}$ and bolls $plant^{-1}$, however boll weight varied trivially (Table 2). A fertigation level of 100% RDN elucidated better sympodial branches $plant^{-1}$ (19.5), boll weight (3.93 g) and bolls $plant^{-1}$ (58.7) over 75% RDN (17.7, 3.87 g and 53.8, respectively) in conformity with Singh and Bhati (2018). Among N levels, 100% RDN revealed significantly higher SCY by 10% and 25%, over 75% RDN (2975 kg ha^{-1}) and broadcasting method (2626 kg ha^{-1}), respectively. Furthermore, it was elucidated that SSDF of 100% RDN either at 0.8 (3484 kg ha^{-1}) or 1.0 ETc (3550 kg ha^{-1}) resulted in 5.6% and 7.6 % improved yield over SDF of 100% RDN (3298 kg ha^{-1}). These results clearly established that SSDF can play a pivotal role in improving the yield attributes and SCY in comparison to SDI and soil application of nutrients. Improved boll weight and bolls $plant^{-1}$ under SSDF has remained the primary reason for higher SCY. The bolls $plant^{-1}$ was 21.4% and 32.5% higher under SSDF of 75% RDN and 100% RDN, respectively over broadcasting 100% RDN. These findings reveal that both water and nitrogen greatly govern the yield as noticed from the fact that by increasing the water and fertigation level, SCY tends to increase. Significant reduction in yield attributes and SCY was evident under least level of water and nitrogen (i.e. SSDI of 0.6 ETc with a fertigation of 75% RDN), where supply of both water and nitrogen was minimal (Table 4). However, SCY improved significantly by 26%, while increasing irrigation level from 0.6 ETc to 0.8 ETc, whereas there was only a marginal increase of 1 %, while moving from

Table 4. Effect of various treatments on bio-physical water productivity, water use efficiency and nitrogen use efficiency (Pooled means).

	Irrigation regimes (IR)					
Nitrogen fertigation schedules (FS)	**0.6 ETc**	**0.8 ETc**	**1.0 ETc**	**Mean**	**Surface flood (Control 1)**	**Surface drip (Control 2)**
Bio-physical water productivity (kg m^{-3})						
75% RDN	0.58	0.68	0.69	0.65		
100% RDN	0.64	0.68	0.69	0.67		
Mean	0.61	0.68	0.69		0.65	0.71
LSD (p=0.05)	IR = 0.03; FS = NS; IR*FS = NS; IR*FS vs. Controls = 0.01					
Water use efficiency (%)						
75% RDN	78	79	75	77		
100% RDN	80	86	82	82		
Mean	79	82	78		49	80
Nitrogen use efficiency (kg SCY kg^{-1} N)						
75% RDN	29.67	37.99	38.20	35.29		
100% RDN	25.03	30.97	31.56	29.18		
Mean	27.35	34.48	34.88		25.01	29.31
LSD (p=0.05)	IR = 1.59; FS = 1.30; IR*FS = NS; IR*FS vs. Controls = 1.29					

* Where RDN: recommended dose of nitrogen; NS: non-significant; LSD: least significant difference.
Control 1: Surface flood irrigation and soil application of 100 % RDN;
Control 2: Surface drip irrigation @0.8 ETc with fertigation of 100 % RDN

0.8 ETc to 1.0 ETc. Present data revealed that under 100% RDN, SSDI either at 0.8 ETc or 1.0 ETc remained on par for SCY, though it increased by 668 kg ha^{-1} and 734 kg ha^{-1}, respectively over SSDF at 0.6 ETc..

Water productivity indices

Total irrigation water applied was highest under SF (Control 1) i.e 550.0 mm and 400.0 mm for Faridkot and Abohar, respectively and it was 56% and 110% higher in comparison to SSDI at 1.0 ETc (Table 3). However, actual crop evapotranspiration (ET_a) was highest for SSDI at 1.0 ETc with 100% RDN closely followed by SSDI at 0.8 ETc with 100% RDN at both the locations. A general reduction in the range of 4-25% for ET_a could be observed under SF (Control 1) in comparison to SSDI treatments across the locations. Our findings clearly elucidated a saving of 36-54.3% and 52.4-61.4% of irrigation water under SSDI for Faridkot and Abohar, respectively with increased ET_a over SF in conformity with Cetin and Kara (2019). Presented results on savings of water under SSDI are well supported by Patil *et al.* (2009) who observed 45.6% water saving under DI at 1.0 ETc over SF method. Roopashree *et al.* (2016) also reported savings of 21.7% irrigation water under SSDI over SF.

Among studied irrigation regimes (Table 4), improved BPWP values were recorded under SSDI level of 1.0 ETc (0.69 kg m^{-3}), 0.8 ETc (0.68 kg m^{-3}) as well as SDI (0.71 kg m^{-3}), while it was significantly reduced under 0.6 ETc (0.61 kg m^{-3}) and SF (0.65 kg m^{-3}). Reduced BPWP by 10% under SSDI at 0.6 ETc as compared to 0.8 ETc is clearly indicative of its

Table 5. Effect of various treatments on fibre quality parameters (Pooled means)

	Irrigation regimes (IR)					
Nitrogen fertigation schedules (FS)	0.6 ETc	0.8 ETc	1.0 ETc	Mean	Surface flood (Control 1)	Surface drip (Control 2)
Ginning outturn (%)						
75% RDN	32.7	32.8	32.8	32.8		
100% RDN	32.6	32.8	33.6	33.0		
Mean	32.7	32.8	33.2		31.9	32.4
LSD (p=0.05)	IR = NS; FS = NS; IR*FS = NS; IR*FS vs. Controls = NS					
Halo length (mm)						
75% RDN	28.2	28.5	27.5	28.1		
100% RDN	28.4	27.8	27.7	28.0		
Mean	28.3	28.1	27.6		27.0	27.2
LSD (p=0.05)	IR = NS; FS = NS; IR*FS = NS; IR*FS vs. Controls = NS					
Uniformity index						
75% RDN	80.1	80.3	80.1	80.2		
100% RDN	80.3	80.6	80.5	80.5		
Mean	80.2	80.5	80.3		80.3	80.3
LSD (p=0.05)	IR = NS; FS = NS; IR*FS = NS; IR*FS vs. Controls = NS					
Fibre strength (g tex^{-1})						
75% RDN	29.3	30.8	30.4	30.2		
100% RDN	30.0	30.1	29.8	30.0		
Mean	29.6	30.4	30.1		29.1	29.3
LSD (p=0.05)	IR = NS; FS = NS; IR*FS = NS; IR*FS vs. Controls = NS					
Micronaire						
75% RDN	4.1	4.2	4.2	4.2		
100% RDN	4.2	4.2	4.2	4.2		
Mean	4.1	4.2	4.2		4.1	4.2
LSD (p=0.05)	IR = NS; FS = NS; IR*FS = NS; IR*FS vs. Controls = NS					

* Where RDN: recommended dose of nitrogen; NS: non-significant; LSD: least significant difference.
Control 1: Surface flood irrigation and soil application of 100 % RDN;
Control 2: Surface drip irrigation @0.8 ETc with fertigation of 100 % RDN

Table 6. Effect of various treatments on monetary parameters (Pooled means).

	Irrigation regimes (IR)					
Nitrogen fertigation schedules (FS)	**0.6 ETc**	**0.8 ETc**	**1.0 ETc**	**Mean**	**Surface flood (Control 1)**	**Surface drip (Control 2)**
Cost of cultivation ($ ha^{-1})						
75% RDN	940.6	943.8	946.9	943.7		
100% RDN	945.7	948.8	952.0	948.8		
Mean	943.1	946.3	949.4		953.5	948.7
Gross returns ($ ha^{-1})						
75% RDN	2037.2	2457.1	2535.5	2343.2		
100% RDN	2272.5	2699.5	2759.2	2577.0		
Mean	2154.8	2578.3	2647.3		2096.2	2564.8
Net Returns ($ ha^{-1})						
75% RDN	1096.5	1513.2	1588.5	1399.4		
100% RDN	1326.8	1750.6	1807.2	1628.2		
Mean	1211.6	1631.9	1697.8		1142.7	1616.0
B:C ratio						
75% RDN	1.16	1.60	1.67	1.47		
100% RDN	1.40	1.84	1.89	1.71		
Mean	1.28	1.72	1.78		1.19	1.70
Economic water productivity ($ m^{-3})						
75% RDN	0.25	0.32	0.33	0.30		
100% RDN	0.30	0.34	0.35	0.33		
Mean	0.27	0.33	0.34		0.28	0.34

* Where 1US $=75INR, Rate of seed cotton=0.75US $ kg^{-1}; SSDI: sub-surface drip irrigation
RDN: recommended dose of nitrogen; NS: non-significant; LSD: least significant difference.
Control 1: Surface flood irrigation and soil application of 100 % RDN;
Control 2: Surface drip irrigation @0.8 ETc with fertigation of 100 % RDN

poor efficiency in agreement with Singh et al. (2018), who elucidated least water productivity under SDI at 0.6 ETc (0.95 kg m^{-3}). SF method revealed least WUE (49%), while values were considerably improved under SSDI level of 0.8 ETc (82%), closely followed by SDI (80%), SSDI level of 0.6 ETc (79%) and 1.0 ETc (78%). Nevertheless, WUE under SF was 38%, 40% and 37% lower as compared to SSDI levels of 0.6 ETc, 0.8 ETc and 1.0 ETc, respectively. Better WUE under SDI/SSDI at 0.8 ETc was in conformity with Shruti and Aladakatti (2017), who elucidated higher values under DI at 0.8 ETc over other irrigation levels.

Among fertigation levels, 100% RDN recorded numerically higher BPWP of 0.67 kg m^{-3} over 75% RDN and surface flood. However, SSDF of 75% and 100% RDN exhibited better WUE over broadcasting fertilizer (49%) in line with Jayakumar *et al.* (2015) who reported higher WUE (0.64 kg m^{-3}) under DF of 100% recommended nutrients over conventional method (0.32 kg m^{-3}). These results clearly established that SSDF of either 0.8 or 1.0 ETc along with 100% RDN recorded better BPWP and WUE over SF method primarily due to increased SCY despite limited application of water. Thus, current findings could elucidate that SSDF at 0.8 ETc can become an effective tool for increasing the cotton productivity as well as water use efficiency without sacrificing SCY (FernÃ¡ndez *et al.,* 2020).

Nitrogen use efficiency

Nitrogen is one of the most important limiting factor governing the growth and productivity of the crop plants. Present findings clearly established a reduction in the NUE with each increase in N level. Within irrigation regimes, SSDI of 1.0 ETc (34.88 kg SCY kg^{-1} N) recorded higher NUE closely followed by 0.8 ETc (34.48 kg SCY kg^{-1} N), while 0.6 ETc resulted in significantly lowest (27.35 kg SCY kg^{-1} N). Further, NUE under SF (Control 1) was 9%, 27% and 28% lesser as compared to SSDI of 0.6 ETc, 0.8 ETc and 1.0 ETc, respectively (Table 4).

Among fertigation levels, SSDF of 75% RDN (35.29 kg SCY kg^{-1} N) recorded statistically better NUE by 20.9 % over 100% RDN (29.18 kg SCY kg^{-1} N) in line with Singh et al. (2018) who observed 27% higher NUE under 75% RDN over 100% RDN. However, both SSDF levels of 75% RDN and 100% RDN exhibited increased NUE by 17% and 41%, respectively over conventional urea broadcasting (25.01 kg SCY kg^{-1} N). Presented results therefore clearly established the superiority of SSDF in the efficient use of N in comparison to conventional method. Higher NUE under SSDF was primarily due to application of nitrogen directly to the root zone which in turn improved yield. Moreover, split application under SSDF might have checked the N losses in the soil in comparison to only two splits under broadcasting method which further helped to enhance NUE in proximity with Joshi et al.(2015), wherein 47% higher efficiency was observed under fertigation as compared to soil application.

Fibre quality parameters

Different treatments failed to mark any significant and consistent effect on fibre quality parameters such as ginning outturn, halo length, micronaire, uniformity index and fibre strength (Table 5).

Economics

Highest gross return ($2759.2 ha^{-1}), net returns ($1807.2 ha^{-1}) and B:C ratio (1.89) were recorded under the treatment receiving SSDF at 1.0 ETc with fertigation of 100% RDN. However, SSDI of 0.8 ETc with 100% RDN recorded little lesser ($1750.6) net returns by $56.6 ha^{-1}, but with an additional saving of 20% irrigation water (Table 6). These findings get fair support from Aladakatti *et al.* (2012) and Pawar *et al.* (2015). Statistically lowest gross returns ($2037.2 ha^{-1}), net returns ($1096.6 ha^{-1}) and B:C ratio (1.16) was observed under SSDI at 0.6 ETc with 75% RDN, thus making it to be least remunerative among studied drip treatments. Nevertheless, SSDI at 0.8 ETc with 100% RDN recorded significant increase of 53% higher net returns over SF method. Reduced B: C under conventional practice of SF method (1.19) further substantiated that fertilizer and water application through SSDF is much more rewarding under north-western Indian conditions in conformity with Neelakanth *et al.* (2019) who reported 16% higher net returns under SSDI over SF irrigation.

Economic water productivity (EWP) remained higher under SSDI level of 1.0 ETc and SDI closely followed by SSDI of 0.8 ETc, while least values were exhibited under 0.6 ETc ($0.27 m^{-3}) and SF method ($0.28 m^{-3}). EWP under SF was lower by 15% and 18%, respectively over SSDI levels of 0.8 ETc and 1.0 ETc, which indicated it to be inferior as compared to other treatments. Among fertigation levels, SSDF of 100% RDN ($0.33 m^{-3}) recorded better EWP over 75% RDN ($0.30 m^{-3}). However, both SSDF levels of 75% and 100% RDN exhibited increased EWP by 7% and 15%, respectively over Control 1 ($0.28 m^{-3}). SSDF of 0.8 ETc with 100% RDN and 1.0 ETc with 100% RDN recorded 21% and 25 higher EWP over conventional method. These findings clearly elucidated the advantage of SSDF in increasing monetary advantage over the crop raised under traditional method. It is concluded that for higher seed cotton yield, a SSDF combination of 0.8 ETc along with 112.5 kg N ha^{-1} should be adopted by farmers to improve SCY and better net returns.

Authors' contribution

Conceptualization of research work and designing of experiments (KS); Execution of field/lab experiments and data collection (PS,MS); Analysis of data and interpretation (KS,ASB,PS);Preparation of manuscript (KS, PS, ASB)

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