



RESEARCH ARTICLE

Influence of subsurface drip lateral depth and irrigation-nitrogen fertigation regimes on growth and productivity of high-density planting system cotton

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Received: 09 June 2026; Accepted: 14 July 2026; Available online: Version 1.0: 01 August 2026

Cite this article: Sivanesan M, Somasundaram S, Raju M, Anantharaju P, Bharathi RS, Rani T. Influence of subsurface drip lateral depth and irrigation-nitrogen fertigation regimes on growth and productivity of high-density planting system cotton. Plant Science Today. 2026; 13(sp5): 1-13. <https://doi.org/10.14719/pst.15971>

Abstract

Water scarcity necessitates the adoption of advanced irrigation technologies such as subsurface drip irrigation (SSDI) to enhance cotton productivity under the high-density planting system (HDPS). A field experiment was conducted at Tamil Nadu Agricultural University, Coimbatore, during the summer 2025 and winter 2025–26 seasons to optimise subsurface drip irrigation lateral depth and nitrogen fertigation for HDPS cotton. The experiment was laid out in a strip plot design with four lateral placement depths (0, 10 ± 2, 20 ± 2 and 30 ± 2 cm) and four irrigation-nitrogen fertigation combinations, replicated 3 times. Subsurface lateral placement at 30 ± 2 cm recorded the highest seed cotton yield of 2704.25 and 2790.55 kg ha⁻¹ during the summer and winter seasons, respectively. Likewise, irrigation at 1.0 crop evapotranspiration (ET_c) combined with 100 kg nitrogen (N) ha⁻¹ produced the highest yields of 2615.55 and 2665.87 kg ha⁻¹. The combination of 30 ± 2 cm lateral placement, 1.0 ET_c irrigation and 100 kg N ha⁻¹ fertigation increased seed cotton yield by 39.5 % in summer and 47.3 % in winter compared with surface lateral placement (0 cm) receiving 0.75 ET_c + 75 kg N ha⁻¹. Therefore, subsurface lateral placement at 30 ± 2 cm with irrigation at 1.0 or 0.75 ET_c and 100 kg N ha⁻¹ can be recorded superior growth, yield attributes and productivity of HDPS cotton under subsurface drip irrigation conditions.

Keywords: cotton; high-density planting system; lateral placement depth; nitrogen fertigation; seed cotton yield; subsurface drip irrigation

Introduction

Cotton (*Gossypium* spp.) is widely recognised as one of the most significant fibre crops supporting agricultural economies and the world's textile industry. The crop is known as the "king of fibre" and "white gold" because of its significant contributions to industrial growth, international trade and rural livelihoods (1). Cotton is grown on around 33 million hectares worldwide and in recent years, it has produced 25–26 million tonnes of lint annually (1, 2). India accounts for approximately 23–24 % of the world's cotton production and has the largest acreage under cotton cultivation. During the 2023–24 season, the country produced about 31.6 million bales, supporting the livelihoods of millions of farmers and workers involved in the textile value chain (3). Cotton productivity is still very low in some areas despite its economic significance because of factors like water shortage, climate variability and ineffective resource management.

Water scarcity has become a critical challenge to agricultural sustainability, largely driven by climate variability, irregular rainfall, over-extraction of groundwater and rising water demands from multiple sectors. Agriculture is the largest consumer of freshwater, accounting for nearly 70 % of global freshwater withdrawals (4) and approximately 80 % of total freshwater use in

India (5). In addition, the steady decline in per capita freshwater availability (1) has further aggravated the situation. Cotton, being a long-duration crop, is particularly sensitive to water stress, especially during key growth stages such as flowering and boll formation. Moisture deficit during these stages can reduce nutrient absorption, impair boll development and ultimately lower yield and fibre quality which affects the overall economic viability of cotton production systems (6).

The adoption of efficient irrigation technologies is essential to overcome these challenges by enhancing irrigation efficiency and ensuring sustainable crop production. Subsurface drip irrigation (SSDI) is one of the water-saving technologies that has become popular for increasing crop output and water use efficiency. In contrast to traditional surface irrigation, SSDI distributes water directly into the crop root zone, reducing evaporation losses and enhancing the even distribution of soil moisture (6). This approach maintains ideal soil moisture levels for crop growth while making better use of scarce water resources. The efficiency of water distribution within the soil profile in SSDI systems is significantly influenced by the lateral placement depth. Root development, nutrient mobility, soil wetting patterns and overall crop performance are all impacted by lateral depth (7).

To maximise irrigation efficiency, drip laterals must be placed appropriately. While deeper placement might enhance crop water intake and improve moisture availability within the active root zone, shallow lateral placement may increase evaporation losses and stimulate surface root development. Research has shown that, in comparison to shallow lateral depths of 0–10 cm, deeper lateral placement of 20–30 cm generally enhances water use efficiency, root development and nutrient uptake in cotton. Better root-zone moisture conditions boost plant physiological processes, which in turn lead to increased cotton production and better fibre quality (8).

The ability to apply fertiliser using irrigation water, a process termed fertigation, is another significant benefit of SSDI. Fertigation improves nutrient availability and lowers losses through leaching or volatilisation by precisely and promptly supplying nutrients directly to the root zone. Nitrogen is one of the key nutrients needed for cotton growth and it has a significant impact on crop growth, canopy development, boll formation and lint yield. For cotton farming to be as productive as possible, nitrogen control must be optimised. Fertigation increases the efficiency of nitrogen usage by matching crop demand with nutrient delivery. According to earlier research, when compared to traditional fertiliser application techniques, optimal nitrogen delivery using drip fertigation greatly improved growth characteristics, boll development and seed cotton output (8, 9).

In contemporary cotton farming techniques, plant population control has become more crucial in addition to effective water and fertiliser management. The high-density planting system (HDPS) has been a viable strategy for raising cotton productivity per unit area in recent years. To optimise light interception inside the crop canopy and alter canopy architecture, HDPS entails growing cotton at higher plant densities. Under HDPS, sympodial branching is increased and monopodial branch development is typically decreased, leading to better boll dispersal and effective canopy management. Additionally, HDPS makes mechanised processes easier, especially mechanical harvesting, which lowers labour costs and boosts total productivity (10).

Despite extensive research on drip irrigation and fertigation in cotton, limited attention has been given to the combined influence of SSDI lateral depth, irrigation scheduling and nitrogen fertigation under HDPS, particularly under tropical conditions. These management practices collectively regulate root-zone dynamics by influencing soil moisture distribution, root proliferation, nutrient availability and nutrient uptake efficiency. Optimising lateral placement depth ensures effective moisture delivery within the active root zone, while irrigation scheduling based on crop evapotranspiration (ETc) maintains adequate soil water availability during critical growth stages. Simultaneously, nitrogen fertigation synchronises nutrient supply with crop demand, thereby improving nutrient-use efficiency and minimising losses. Understanding these interactions is essential for enhancing water and nutrient use efficiency while sustaining cotton productivity under HDPS. However, information on their integrated effects under tropical conditions remains limited. Therefore, the present study was undertaken to evaluate the interactive effects of subsurface drip irrigation lateral depths, irrigation levels based on ETc and nitrogen fertigation on the growth, yield attributes and yield of HDPS cotton.

Materials and Methods

Experimental site

A field experiment was carried out during summer 2025 and winter 2025–26 in the wetland farms of Tamil Nadu Agricultural University, Coimbatore. The trial site is located at 11.001° N latitude and 76.923° E longitude with an elevation of 426.7 m above mean sea level, which is classified under the western agricultural climate zone of Tamil Nadu. The experimental field was characterised by a typical Haplustalf soil belonging to the Noyyal series. The soil exhibited a pH of 8.1 during the summer season and 7.6 during the winter season, while the electrical conductivity measured 0.41 and 0.17 dS m⁻¹, respectively. The bulk density of the soil is 1.33 and 1.37 mg m⁻³, respectively. The soil nutrient status showed available nitrogen levels of 203 and 212 kg ha⁻¹, available phosphorus levels of 16 and 18 kg ha⁻¹ and available potassium levels of 429 and 421 kg ha⁻¹ during both seasons (Fig. 1).

The weather conditions during the summer 2025 season were characterised by a mean daily rainfall of 1.66 mm, maximum temperature of 31.19 °C, minimum temperature of 22.60 °C, relative humidity of 78.63 % and wind speed of 2.50 m s⁻¹. During the winter 2025–26 season, the mean daily rainfall was 1.10 mm, maximum temperature of 29.21 °C, minimum temperature of 18.84 °C, relative humidity of 79.24 % and wind speed of 1.89 m s⁻¹.

Experimental design and treatments

The field experiment was laid out in a strip plot design with 3 replications. Each replication (block) was divided into four vertical strips assigned to the subsurface drip lateral depth treatments and four horizontal strips assigned to the irrigation-nitrogen fertigation treatments. The intersection of the vertical and horizontal strips constituted the treatment plots and the treatments were randomly allocated within each replication.

The details of the experiment are provided in Table 1.

Table 1. Treatment details

Vertical strip	Horizontal strip
Lateral placement depth	Irrigation-N fertigation levels
L ₁ - 0 cm	N ₁ - 1.0 ETc + 100 kg N
L ₂ - 10 ± 2 cm	N ₂ - 1.0 ETc + 75 kg N
L ₃ - 20 ± 2 cm	N ₃ - 0.75 ETc + 100 kg N
L ₄ - 30 ± 2 cm	N ₄ - 0.75 ETc + 75 kg N

L₁–L₄: lateral placement depth (cm); ETc: crop evapotranspiration; N: N fertigation levels (kg ha⁻¹).

Crop management

Cotton variety VPT 2, which was cultivated under a HDPS with a spacing of 90 × 15 cm. Other management practices were followed according to local agronomic recommendations

Irrigation scheduling

Irrigation scheduling was implemented based on the procedure outlined previously (11). The amount of irrigation water required was determined each day by utilising the recorded Class A pan evaporation data along with appropriate pan coefficient values and crop coefficients corresponding to different growth stages of the crop.

$$ETc = Eo \times Kp \times Kc \quad \text{Eq. (1)}$$

Where,

ETc - Crop evapotranspiration (mm day⁻¹)

Eo - Pan evaporation (mm day⁻¹)

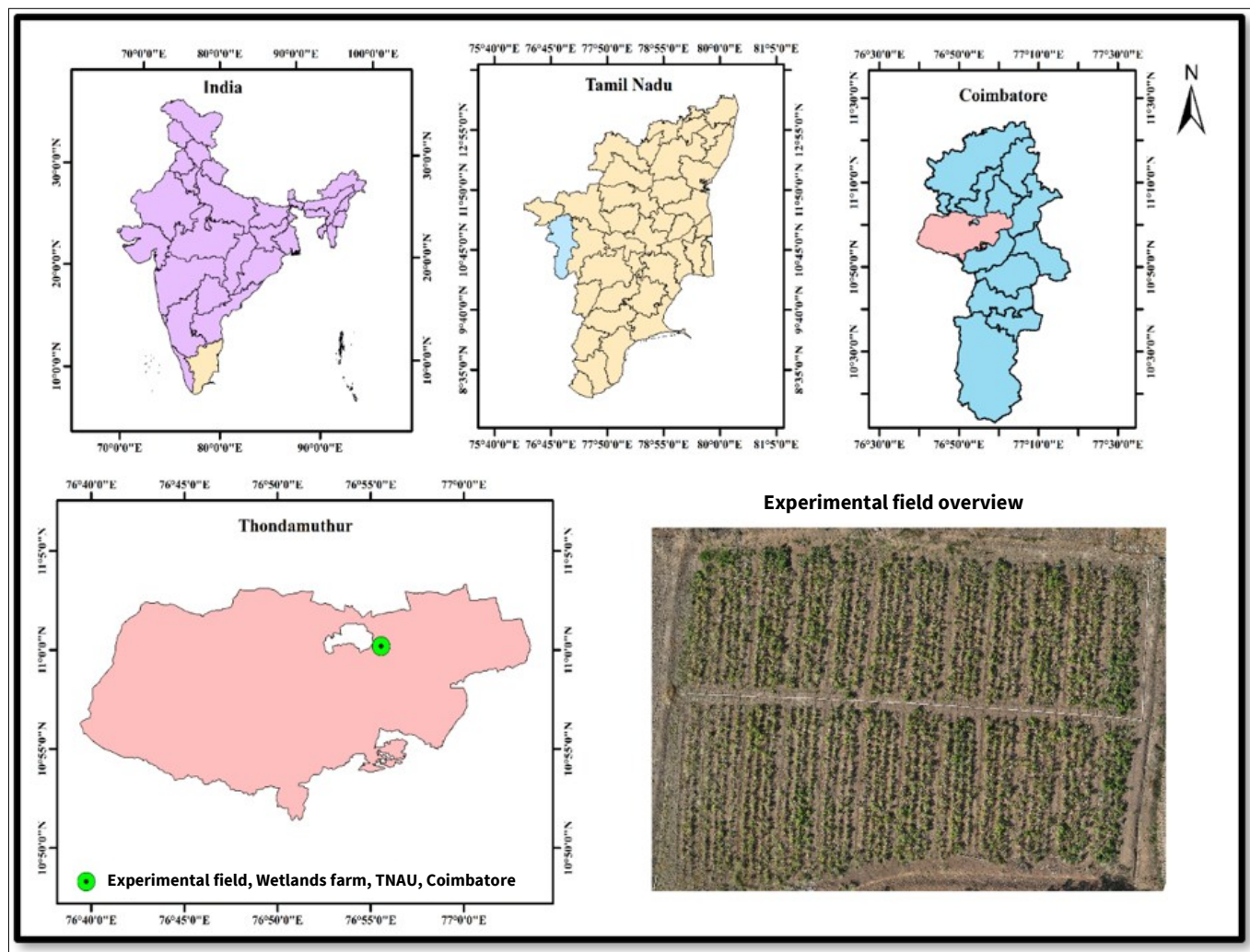


Fig. 1. Location of the experimental field of cotton.

Source: Survey of India (SOI) base maps.

Kp- Pan coefficient (0.8)

Kc- Crop coefficient

The daily irrigation water requirement for the cotton crop was calculated using the following equation.

$$IR = ET_c - Re \quad \text{Eq. (2)}$$

Where,

IR- Net depth of irrigation (mm day^{-1})

Re- Effective rainfall (mm day^{-1})

Pan evaporation data were collected from the Agro Climate Research Centre, Agro-meteorological Observatory of Tamil Nadu Agricultural University, Coimbatore. Irrigation scheduling was performed at three-day intervals according to the respective treatment schedules. The volume of irrigation water to be applied was estimated by subtracting the effective rainfall from the calculated crop evapotranspiration. Effective rainfall was determined using the water balance method suggested by Dastane (12). The irrigation duration required for each treatment was then calculated using the following formula.

Volume of water for each treatment plot (l)

$$= \text{Area (m}^2\text{)} \times \text{Depth (m)} \times 1000 \quad \text{Eq. (3)}$$

Irrigation duration (hr) =

$$\frac{\text{Volume of water for each treatment plot (L)}}{\text{No. of dripper in the plot} \times \text{discharge rate (lph)}} \quad \text{Eq. (4)}$$

The crop coefficient values of cotton were illustrated in Table 2.

Table 2. Kc value of cotton (13)

Stage	Kc value
Seedling (0–25 DAS)	0.4–0.5
Vegetative (26–75 DAS)	0.7–0.8
Reproductive (76–120 DAS)	1.0–1.2
Maturity (121–150 DAS)	0.8–0.9

Kc: crop coefficient; DAS: days after sowing.

Fertiliser management

The recommended fertiliser dose for HDPS cotton was $100 : 50 : 50 \text{ kg N, P}_2\text{O}_5 \text{ and K}_2\text{O ha}^{-1}$. Nitrogen, phosphorus and potassium were applied using urea (46 % N), single superphosphate (16 % P_2O_5) and muriate of potash (60 % K_2O), respectively.

For treatments N_1 and N_3 , nitrogen was applied through fertigation at a rate of 100 kg ha^{-1} , whereas treatments N_2 and N_4 received nitrogen through fertigation at a rate of 75 kg ha^{-1} . A basal dose consisting of 25 % nitrogen, 25 % potassium and the full recommended dose of phosphorus was applied to the soil before sowing. The remaining 75 % nitrogen and 75 % potassium was supplied through subsurface drip fertigation during the crop growth period. The detailed fertigation schedule followed for cotton is presented in Table 3.

Table 3. Fertigation schedule for cotton (kg ha⁻¹)

Crop growth phase	Fertiliser phase (DAS)	N ₁ and N ₃ (100 kg ha ⁻¹) N alone	N ₂ and N ₄ (75 kg ha ⁻¹) N alone	K
Basal				
Germination phase	0–15	25	19	12.5
Fertigation				
Vegetative phase	16–25	15.6	11.7	4.9
	26–35	15.6	11.7	4.9
	36–45	15.6	11.7	4.9
	46–55	-	-	-
Flowering phase	56–65	7.8	5.7	5.5
	66–75	7.8	5.7	5.5
	76–87	7.6	5.7	5.5
	88–97	-	-	-
Maturity phase	98–107	2.5	1.9	3.2
	108–117	2.5	1.9	3.1

DAS: days after sowing; N: N fertigation levels (kg ha⁻¹); K: potassium (kg ha⁻¹).

Assessment of growth parameters

Plant height was measured from the base of the plant to the tip of the longest leaf. The plants were carefully uprooted from the field, oven-dried at 70 °C for 48 hr and weighed to determine their dry weight. The leaf area of the plants was measured using a LI-COR 3000 leaf area meter (14).

Yield parameters and yield

The sympodial branches per plant, number of bolls per plant, boll weight and seed cotton yield were recorded at harvest. Harvested bolls were air-dried until the moisture content was reduced to below 11 %. The mean boll weight was determined by dividing the total weight of a representative sample of bolls by the number of bolls in that sample. Seed cotton was harvested from each experimental plot and the yield obtained was subsequently converted and expressed on a kilogram per hectare (kg ha⁻¹) basis.

Statistical analysis

The data recorded for various parameters were subjected to analysis of variance (ANOVA) using R software version 4.2.0 (RStudio 2022.02.3 + 492) following the procedure appropriate for a strip plot design. Prior to analysis, the assumptions of normality of residuals and homogeneity of variance were examined and found to be satisfactory. Treatment means were compared using the least significant difference (LSD) test at the 5 % level of probability whenever the *F*-test was significant.

Results

Plant height (cm)

Generally, a steady and progressive increase in plant height was observed from 30 days after sowing (DAS) up to the harvest stage (135 DAS). Lateral placement depths and irrigation-nitrogen fertigation levels significantly ($p \leq 0.05$) influenced the plant height of cotton during both seasons.

Among the different lateral placement depths, plant height did not differ significantly at the early growth stage (30 DAS).

However, from 60 DAS to harvest, significant differences in plant height were observed during both seasons. Taller plants were recorded under lateral placement depth of 30 + 2 cm (L₄) with plant heights of 53.38, 89.86 and 96.07 cm during the first season and 60.22, 87.37 and 104.00 cm during the second season at 60, 90 DAS

and harvest, respectively. This treatment was statistically on par with lateral placement depth of 20 + 2 cm (L₃), which recorded plant heights of 52.20, 84.88 and 95.79 cm in the first season and 58.85, 87.05 and 102.41 cm in the second season, respectively. The shortest plants were observed under surface lateral placement at 0 cm depth (L₁), which recorded plant heights of 43.28, 68.65 and 81.99 cm during the first season and 48.84, 79.67 and 94.99 cm during the second season, respectively.

Irrigation and nitrogen fertigation levels did not significantly influence plant height at 30 DAS. However, significant differences were observed from 60 DAS to harvest stage during both seasons.

At 60 DAS, the maximum plant height was recorded under 1.0 ETc with 100 kg N (N₁), which registered 51.25 and 57.52 cm during the first and second seasons, respectively and was statistically on par with 0.75 ETc with 100 kg N (N₃), which recorded 50.15 and 56.83 cm, respectively. The minimum plant height was recorded under 0.75 ETc with 75 kg N (N₄).

At 90 DAS and harvest stage, significantly taller plants were observed under 1.0 ETc with 100 kg N (N₁), which recorded plant heights of 83.41 and 93.21 cm during the first season and 87.45 and 102.17 cm during the second season, respectively. This treatment was statistically on par with 0.75 ETc with 100 kg N (N₃), which recorded 79.12 and 92.33 cm during the first season and 86.85 and 100.75 cm during the second season, respectively. The shortest plants were recorded under 0.75 ETc with 75 kg N (N₄) during both seasons.

The interaction effect between lateral placement depths and irrigation-nitrogen fertigation levels was found to be non-significant at all growth stages during both seasons (Table 4).

Leaf area index

The leaf area index (LAI) of cotton was significantly influenced ($p \leq 0.05$) by lateral placement depths during the later growth stages (60 DAS to harvest) in both seasons. Among the lateral placement depths, the highest LAI was recorded under lateral placement depth of 30 ± 2 cm (L₄), which registered values of 4.10, 2.34 and 1.84 during the first season and 4.66, 2.63 and 2.03 during the second season at 60, 90 DAS and harvest stage, respectively. This treatment was statistically on par with lateral placement depth of 20 ± 2 cm (L₃), which recorded LAI values of 4.09, 2.29 and 1.83 in the first season and 4.61, 2.60 and 2.00 in the second season, respectively. The lowest LAI was observed under surface lateral placement at 0 cm depth (L₁), which recorded values of 3.71, 2.01 and 1.64 during the first season and 4.25, 2.22 and 1.83 during the second season, respectively.

Irrigation and nitrogen fertigation levels also significantly influenced the LAI during the later growth stages of the crop. At 60 DAS, the highest LAI was recorded under 1.0 ETc with 100 kg N (N₁), which registered values of 4.09 and 4.66 during the first and second seasons, respectively. This treatment was statistically comparable with 0.75 ETc with 100 kg N (N₃), which recorded LAI values of 4.06 and 4.58, respectively. The lowest LAI was observed under 0.75 ETc with 75 kg N (N₄), which recorded values of 3.71 and 4.25 during the first and second seasons, respectively.

During the later growth stages (90 DAS to harvest), the highest LAI was observed under 1.0 ETc with 100 kg N (N₁), which recorded values of 2.34 and 1.84 during the first season and 2.63 and 2.03 during the second season, respectively. This treatment

Table. 4. Effect of lateral placement depths and irrigation-nitrogen fertigation levels on plant height (cm) during summer (S I) and winter (S II)

Treatments	Plant height (cm)							
	30 DAS		60 DAS		90 DAS		At harvest	
	S I	S II	S I	S II	S I	S II	S I	S II
Lateral placement depths								
L ₁	29.38	33.09	43.28	48.84	68.65	79.67	81.99	94.99
L ₂	28.93	32.34	46.52	52.36	74.11	83.05	87.12	97.10
L ₃	27.68	30.99	52.20	58.85	84.88	87.05	95.79	102.41
L ₄	26.43	28.66	53.38	60.22	89.86	87.37	96.07	104.00
SEd	0.87	1.30	0.82	0.94	2.13	2.02	2.05	1.69
CD(<i>p</i> = 0.05)	NS	NS	2.00	2.29	5.20	4.95	5.01	4.13
Irrigation-N fertigation levels								
N ₁	29.00	32.51	51.25	57.52	83.41	87.45	93.21	102.17
N ₂	27.95	30.19	47.73	53.47	78.55	82.52	89.73	97.97
N ₃	28.40	31.60	50.15	56.83	79.12	86.85	92.33	100.75
N ₄	27.06	30.77	46.25	52.46	76.40	80.31	85.70	97.59
SEd	0.74	0.98	0.98	1.11	1.90	2.03	1.98	1.33
CD(<i>p</i> = 0.05)	NS	NS	2.39	2.71	4.65	4.96	4.84	3.26
Lateral depths × Irrigation- N fertigation levels								
SEd	1.45	1.78	2.54	2.87	4.72	4.48	3.99	3.36
CD(<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation- N fertigation levels × Lateral depths								
SEd	1.38	1.56	2.60	2.93	4.62	4.48	3.96	3.19
CD(<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

L₁–L₄: lateral placement depth (cm); DAS: days after sowing; SI: summer season I; SII: winter season II; ETC: crop evapotranspiration; N: N fertigation levels; SEd: standard error of difference; CD: critical difference; NS: not significant at *p* = 0.05.

was statistically on par with 0.75 ETC with 100 kg N (N₃), which recorded LAI values of 2.29 and 1.83 during the first season and 2.60 and 2.00 during the second season, respectively. The lowest LAI was recorded under 0.75 ETC with 75 kg N (N₄) during both seasons.

The interaction effect between lateral placement depths and irrigation-nitrogen fertigation levels on LAI was non-significant at all growth stages in both seasons (Table 5).

Dry matter production (kg ha⁻¹)

The dry matter production (DMP) of cotton was significantly influenced (*p* ≤ 0.05) by lateral placement depths and irrigation-nitrogen fertigation levels during the later growth stages of the crop. However, at the early growth stage (30 DAS), no significant differences were observed.

Among the lateral placement depths, significantly higher dry matter production was recorded under lateral placement depth of 30 ± 2 cm (L₄) from 60 DAS to harvest stage. It registered DMP values of 4390.25, 8811.75 and 11374.70 kg ha⁻¹ during the first season and 4938.49, 8901.62 and 11671.34 kg ha⁻¹ during the second season at 60, 90 DAS and harvest stage, respectively. This treatment was statistically on par with lateral placement depth of 20 ± 2 cm (L₃), which recorded 4132.17, 8413.74 and 10806.33 kg ha⁻¹ during the first season and 4666.26, 8458.63 and 10968.84 kg ha⁻¹ during the second season, respectively. The lowest DMP was observed under surface lateral placement at 0 cm depth (L₁) during both seasons.

Irrigation and N fertigation levels also significantly influenced dry matter production during the later growth stages. At

Table. 5. Effect of lateral placement depths and irrigation–nitrogen fertigation levels on Leaf area index during summer (S I) and winter (S II)

Treatments	Leaf area index							
	30 DAS		60 DAS		90 DAS		At harvest	
	S I	S II	S I	S II	S I	S II	S I	S II
Lateral placement depths								
L ₁	0.99	1.12	3.71	4.25	2.01	2.22	1.64	1.83
L ₂	0.99	1.11	3.89	4.26	2.14	2.36	1.81	1.97
L ₃	0.97	1.09	4.09	4.61	2.29	2.60	1.83	2.00
L ₄	0.97	1.08	4.10	4.66	2.34	2.63	1.84	2.03
SEd	0.02	0.02	0.18	0.10	0.04	0.06	0.05	0.04
CD (<i>p</i> = 0.05)	NS	NS	0.44	0.24	0.10	0.15	0.12	0.10
Irrigation-N fertigation levels								
N ₁	1.00	1.12	4.09	4.66	2.28	2.53	1.84	2.02
N ₂	0.98	1.09	3.98	4.29	2.14	2.47	1.75	1.95
N ₃	0.99	1.09	4.06	4.58	2.25	2.51	1.82	1.98
N ₄	0.98	1.09	3.67	4.25	2.11	2.31	1.71	1.88
SEd	0.02	0.02	0.11	0.10	0.05	0.05	0.03	0.04
CD (<i>p</i> = 0.05)	NS	NS	0.27	0.23	0.12	0.12	0.06	0.09
Lateral depths × Irrigation- N fertigation levels								
SEd	0.05	0.06	0.32	0.35	0.11	0.15	0.12	0.10
CD (<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation- N fertigation levels × Lateral depths								
SEd	0.05	0.06	0.28	0.35	0.12	0.14	0.12	0.10
CD (<i>p</i> = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

L₁–L₄: lateral placement depth (cm); DAS: days after sowing; SI: summer season I; SII: winter season II; ETC: crop evapotranspiration; N: N fertigation levels; SEd: standard error of difference; CD: critical difference; NS: not significant at *p* = 0.05.

60 DAS, the highest DMP was recorded under 1.0 ETc with 100 kg N (N_1), which registered 4319.58 and 5034.44 kg ha⁻¹ during the first and second seasons, respectively. This treatment was statistically on par with 0.75 ETc with 100 kg N (N_3), which recorded 3960.08 and 4708.13 kg ha⁻¹, respectively. The lowest DMP was observed under 0.75 ETc with 75 kg N (N_4) during both seasons.

During the later stages (90 DAS to harvest), significantly higher DMP was observed under 1.0 ETc with 100 kg N (N_1), which recorded 8589.99 and 10940.95 kg ha⁻¹ during the first season and 8665.90 and 11114.18 kg ha⁻¹ during the second season, respectively. This treatment was statistically comparable with 0.75 ETc with 100 kg N (N_3), which recorded 8083.70 and 10345.69 kg ha⁻¹ during the first season and 8143.55 and 10489.61 kg ha⁻¹ during the second season, respectively. The lowest DMP was recorded under 0.75 ETc with 75 kg N (N_4) during both seasons.

The interaction effect between lateral placement depths and irrigation-nitrogen fertigation levels was found to be non-significant at all growth stages of the crop during both seasons (Fig 2. A and B).

Yield attributes (Sympodial branches per plant, number of bolls per plant, boll weight (g))

Lateral placement depths and irrigation-nitrogen fertigation levels exhibit significant influence ($p \leq 0.05$) on the number of sympodial branches per plant during both seasons of study.

Among different lateral placement depths, the lateral placement depth at 30 ± 2 cm (L_4) produced more sympodial branches per plant (23.17 and 23.89) during both seasons. This was statistically on par with the lateral placement depth at 20 ± 2 cm (L_3) (22.37 and 21.94) during both seasons. The minimum (16.35 and 15.93) sympodial branches per plant were observed in lateral placement depth at 0 cm (L_1) during both seasons.

In respect to the irrigation and N fertigation levels, the treatment 1.0 ETc with 100 kg N (N_1) registered the maximum sympodial branches per plant (21.40 and 21.80), which was statistically on par (20.66 and 20.69) with the treatment 0.75 ETc with 100 kg N (N_3). The minimum sympodial branches per plant (18.17 and 18.06) was observed in the treatment 0.75 ETc with 75 kg N (N_4) during both seasons.

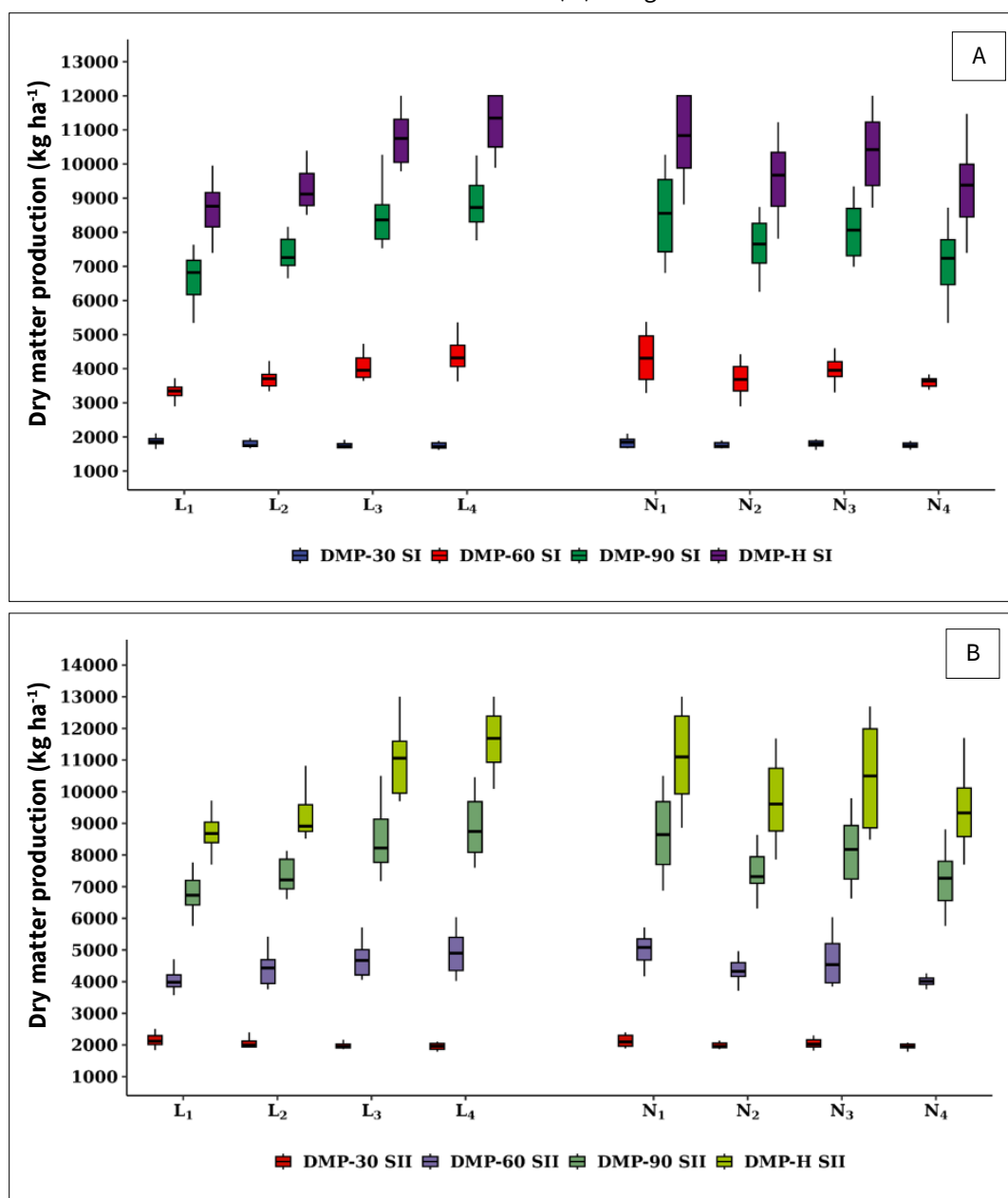


Fig. 2. Effect of lateral placement depth and irrigation–nitrogen fertigation levels on dry matter production (kg ha⁻¹) during (A) summer (SI); (B) winter (SII).

Lateral placement depth and irrigation-nitrogen fertigation levels had a significant interaction on the number of sympodial branches per plant. Invariably, the highest sympodial branches per plant were observed in the (L_4N_3) (25.40), which was statistically on par with (L_4N_1 , L_3N_3 and L_3N_1) (24.90, 24.30 and 23.70) in the summer season. In winter, the highest sympodial branches of per plant (L_4N_1) (26.63) this was statistically on par with (25.27, 25.10 and 24.20) (L_3N_1 , L_4N_3 and L_3N_3) in the winter season. The minimum (16.20 and 13.77) sympodial branches per plant was found in the treatment (L_1N_4) during both seasons.

The lateral placement depths and irrigation-nitrogen fertigation levels had a significant ($p \leq 0.05$) influence on the number of bolls per plant.

In lateral placement depths, the highest number of bolls per plant (9.90 and 10.18) was recorded in the lateral placement depth at 30 ± 2 cm (L_4) and this was comparable with the lateral placement depth at 20 ± 2 cm (L_3) (9.12 and 9.55) during both seasons of the study. The lowest number of bolls (7.33 and 7.58) was observed in lateral placement depth at 0 cm (L_1) during both seasons.

In respect to the irrigation and nitrogen fertigation levels, the treatment 1.0 ETc with 100 kg N (N_1) registered the maximum number of bolls per plant (9.17 and 9.42), which was statistically on par (9.00 and 9.30) with the treatment 0.75 ETc with 100 kg N (N_3). The minimum number of bolls per plant (7.86 and 8.21) was observed in the 0.75 ETc treatment with 75 kg N (N_4) during both seasons.

Table. 6. Effect of lateral placement depths and irrigation-nitrogen fertigation levels on sympodial branches per plant, no. of bolls per plant, boll weight (g) during summer 2025

Treatments	Sympodial branches per plant					No. of bolls per plant					Boll weight (g)				
	N_1	N_2	N_3	N_4	Mean	N_1	N_2	N_3	N_4	Mean	N_1	N_2	N_3	N_4	Mean
L_1	17.03	15.30	16.87	16.20	16.35	7.40	7.20	7.70	7.00	7.33	3.97	4.02	3.97	4.40	4.09
L_2	19.97	16.23	16.07	17.27	17.36	7.87	8.10	8.20	7.30	7.87	4.01	3.83	4.04	4.11	4.00
L_3	23.70	22.10	24.30	19.37	22.37	9.90	8.57	9.60	8.43	9.12	4.03	4.02	3.74	4.06	3.96
L_4	24.90	22.53	25.40	19.83	23.17	11.50	8.90	10.50	8.70	9.90	4.14	3.99	3.77	4.21	4.03
Mean	21.40	19.04	20.66	18.17	19.81	9.17	8.19	9.00	7.86	8.55	4.04	3.96	3.88	4.19	4.02
Interaction	L	N	L × N	N × L		L	N	L × N	N × L		L	N	L × N	N × L	
SEd	0.82	0.63	1.54	1.44		0.40	0.21	0.55	0.45		0.07	0.09	0.29	0.30	
C.D($p = 0.05$)	2.01	1.55	3.38	3.13		0.98	0.51	1.25	0.98		NS	NS	NS	NS	

L_1 – L_4 : lateral placement depth (cm); N: N fertigation levels; L × N: interaction between lateral placement depth and irrigation-nitrogen fertigation level; N × L: interaction between irrigation-nitrogen fertigation level and lateral placement depth; SEd: standard error of difference; CD: critical difference; NS: not significant at $p = 0.05$.

Table. 7. Effect of lateral placement depths and Irrigation- N fertigation levels on Sympodial branches per plant, No. of bolls per plant, Boll weight (g) during winter 2025–26

Treatments	Sympodial branches per plant					No. of bolls per plant					Boll weight (g)				
	N_1	N_2	N_3	N_4	Mean	N_1	N_2	N_3	N_4	Mean	N_1	N_2	N_3	N_4	Mean
L_1	17.83	15.70	16.43	13.77	15.93	7.80	7.40	7.90	7.20	7.58	3.79	4.78	4.88	4.32	4.44
L_2	17.48	17.90	17.03	15.20	16.90	8.07	8.30	8.60	7.60	8.14	4.62	4.57	4.63	3.92	4.43
L_3	25.27	18.44	24.20	19.86	21.94	10.50	8.97	9.90	8.83	9.55	4.59	4.71	4.68	4.75	4.68
L_4	26.63	20.43	25.10	23.40	23.89	11.30	9.40	10.80	9.20	10.18	3.96	4.87	5.02	4.20	4.51
Mean	21.80	18.12	20.69	18.06	19.67	9.42	8.52	9.30	8.21	8.86	4.24	4.73	4.80	4.30	4.52
Interaction	L	N	L × N	N × L		L	N	L × N	N × L		L	N	L × N	N × L	
SEd	0.62	0.76	2.30	2.34		0.37	0.33	0.48	0.45		0.25	0.22	0.59	0.58	
C.D ($p = 0.05$)	1.52	1.86	4.88	4.99		0.91	0.81	1.10	1.02		NS	NS	NS	NS	

L_1 – L_4 : lateral placement depth (cm); N: N fertigation levels; L × N: interaction between lateral placement depth and irrigation-nitrogen fertigation level; N × L: interaction between irrigation-nitrogen fertigation level and lateral placement depth; SEd: standard error of difference; CD: critical difference; NS: not significant at $p = 0.05$.

Lateral placement depths and irrigation-nitrogen fertigation levels had a significant ($p \leq 0.05$) interaction on the number of bolls per plant. Invariably, the highest of bolls per plant were observed in the (L_4N_1) (11.50), which was statistically on par with (L_4N_3) (10.50) in the summer season. In winter, the highest of bolls per plant (L_4N_1) (11.30) was statistically on par with (L_4N_3) (10.80) in the winter season. The minimum (7.00 and 7.20) of bolls per plant was found in the treatment (L_1N_4) during both seasons.

Boll weight is primarily governed by the genetic makeup of the crop and therefore varies mainly among genotypes, while management practices generally have a limited influence on this trait. Consistent with this understanding, the present study revealed no significant effect of lateral placement depth, irrigation-nitrogen fertigation levels, or their interaction on boll weight, indicating that these management factors did not substantially alter boll weight under the experimental conditions (Table 6 and 7).

Seed cotton yield (kg ha⁻¹)

The lateral placement depths and irrigation-nitrogen fertigation levels had a significant ($p \leq 0.05$) effect on the seed cotton yield of the experimental study.

Among lateral placement depths, the highest seed cotton yield (2691.02 kg ha⁻¹) was found in lateral placement depth at 30 ± 2 cm (L_4), which was statistically on par with the lateral placement depth at 20 ± 2 cm (L_3) (2594.69 kg ha⁻¹). The lowest seed cotton yield (2193.16 kg ha⁻¹) was recorded in lateral placement depth at 0 cm (L_1) during both seasons.

In respect to irrigation and nitrogen fertigation levels, the maximum seed cotton yield ($2621.86 \text{ kg ha}^{-1}$) was observed in the treatment 1.0 ETc with 100 kg N (N_1) and this was comparable ($2559.76 \text{ kg ha}^{-1}$) with the treatment 0.75 ETc with 100 kg N (N_3). The minimum seed cotton yield ($2239.18 \text{ kg ha}^{-1}$) was recorded in the treatment the 0.75 ETc treatment with 75 kg N (N_4) during both seasons.

The lateral placement depths and irrigation–nitrogen fertigation levels had a significant interaction in seed cotton yield. In the summer season, the highest seed cotton yield ($2977.37 \text{ kg ha}^{-1}$) was observed in (L_4N_1); this was statistically on par with (L_3N_1 , L_4N_3 and L_3N_3). In the winter season, the maximum seed cotton yield ($3072.81 \text{ kg ha}^{-1}$) was found in (L_4N_1); this was on par with (L_4N_3 , L_4N_1 and L_3N_3). The lowest seed cotton yield (2134.30 and $2047.08 \text{ kg ha}^{-1}$) was recorded in (L_1N_4) during both seasons (Fig. 3).

Discussion

Plant height

The greater plant height observed under subsurface lateral placement at $30 \pm 2 \text{ cm}$ can be attributed to the improved availability of moisture within the effective root zone and reduced evaporative losses. This favourable moisture regime likely promoted better root proliferation, enabling efficient uptake of nutrients and supporting enhanced vegetative growth throughout the crop growth period. Similar observations have been reported in cotton under subsurface drip irrigation, where optimum lateral placement improved root-zone moisture distribution, enhanced root growth and increased plant height compared with surface drip irrigation (15, 16). In contrast, surface placement of laterals (0 cm) might have led to higher evaporation losses and inadequate moisture distribution in the root zone, thereby restricting plant growth at different stages (17).

About irrigation-nitrogen fertigation levels, the application of 1.0 ETc along with 100 kg N ha^{-1} ensured an adequate and continuous supply of both water and essential nutrients, which are

critical for plant growth and development. Nitrogen availability plays a key role in promoting cell division, elongation and chlorophyll synthesis, ultimately resulting in increased plant height. The present findings are also consistent with earlier studies on ETc-based irrigation and nitrogen fertigation, which demonstrated that synchronised water and nitrogen supply through drip irrigation promoted vigorous vegetative growth and improved plant height in cotton (18, 19). On the other hand, reduced irrigation and nitrogen levels ($0.75 \text{ ETc} + 75 \text{ kg N ha}^{-1}$) might have imposed moisture stress and nutrient limitation, thereby adversely affected physiological processes and leading to reduced vegetative growth (20).

Leaf area index

Leaf area index is a key indicator of canopy development, as it reflects the photosynthetically active surface responsible for biomass production. It governs light interception and influences the synthesis and translocation of photo assimilates, thereby maintaining a close relationship with crop productivity (21).

The improvement in LAI under subsurface lateral placement at $30 \pm 2 \text{ cm}$ can be attributed to better soil moisture availability within the root zone and reduced evaporative losses. Such conditions favour sustained leaf expansion and canopy growth throughout the crop period (22). In contrast, surface placement of laterals (0 cm) likely resulted in rapid moisture depletion and uneven water distribution, which restricted leaf development and led to lower LAI (23).

Irrigation-nitrogen fertigation levels also played a crucial role in determining LAI. The application of 1.0 ETc along with 100 kg N ha^{-1} ensured a continuous supply of water and nutrients directly to the root zone, thereby enhancing photosynthetic efficiency and promoting leaf growth. Nitrogen, being an essential component of chlorophyll and proteins, contributes significantly to leaf expansion and canopy formation (18). On the other hand, reduced irrigation and nitrogen levels ($0.75 \text{ ETc} + 75 \text{ kg N ha}^{-1}$) might have imposed moisture stress and nutrient limitation, resulting in restricted leaf expansion and reduced LAI (24).

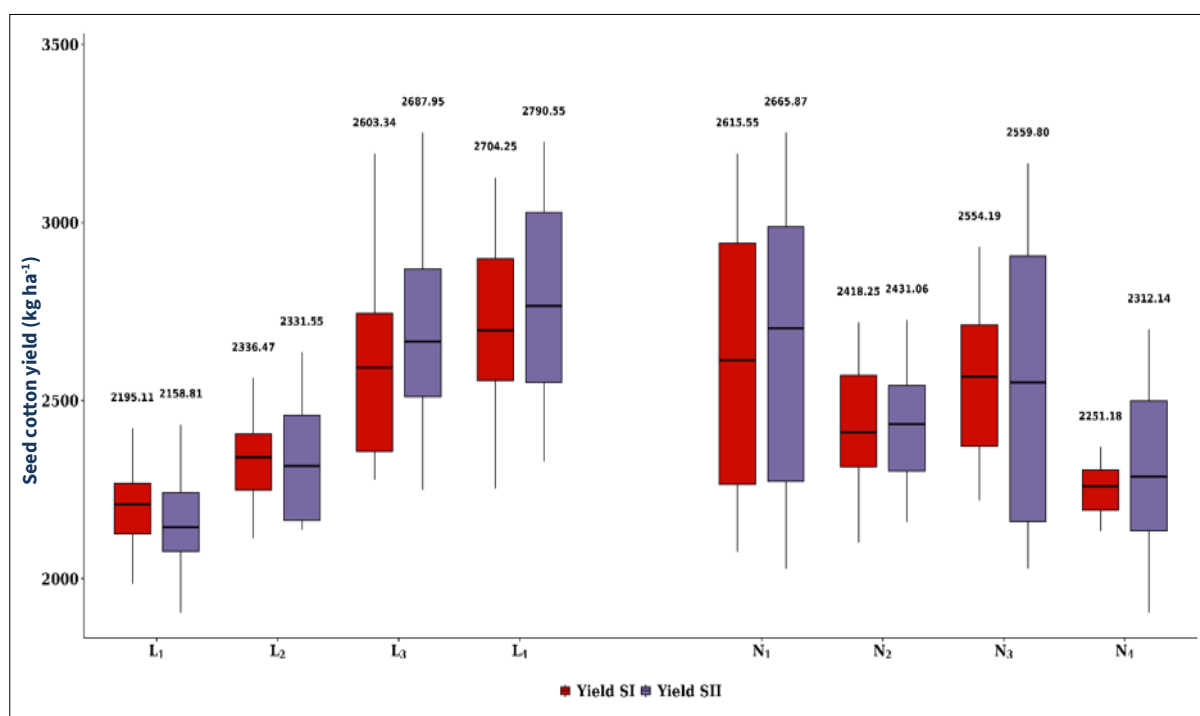


Fig. 3. Effect of lateral placement depths and Irrigation- N fertigation levels on seed cotton yield (kg ha^{-1}) during summer (S I) and winter (S II).

The interaction between lateral depth and irrigation-nitrogen fertigation levels was not significant for LAI, indicating that their individual effects were independent. This suggests that the influence of lateral placement on canopy development remained consistent across different irrigation and nitrogen levels and vice versa. Such a response may be due to the dominant role of adequate moisture and nutrient availability in regulating leaf growth irrespective of their combined treatments (18).

Dry matter production

Dry matter production is a key indicator of crop growth, reflecting the efficiency with which plants utilise available resources for biomass accumulation. It integrates the effects of photosynthesis, nutrient uptake and overall physiological activity and is closely associated with crop productivity (25).

The higher DMP observed under subsurface lateral placement at 30 ± 2 cm can be attributed to improved moisture availability within the root zone and reduced evaporative losses. This favourable soil moisture environment likely supported continuous water supply, enhanced root growth and efficient nutrient uptake, which in turn promoted photosynthetic activity and biomass accumulation. These findings agree with previous studies on subsurface drip irrigation in cotton, which reported that optimum lateral placement improved root-zone moisture availability, enhanced biomass accumulation and increased DMP compared with surface drip irrigation (25, 26). In contrast, surface placement of laterals (0 cm) might have resulted in greater evaporation losses and limited moisture availability, leading to moisture stress and reduced photosynthetic efficiency, thereby lowering DMP (27).

Irrigation-nitrogen fertigation levels also had a pronounced influence on dry matter accumulation. The application of 1.0 ETc along with 100 kg N ha^{-1} ensured an adequate and continuous supply of water and nutrients, which enhanced metabolic activities and supported greater biomass production. Nitrogen plays a vital role in protein synthesis, chlorophyll formation and enzymatic activity, thereby contributing to increased photosynthesis and dry matter accumulation. Comparable results have been reported under ETc-based irrigation and nitrogen fertigation in cotton, where adequate irrigation coupled with the recommended nitrogen dose promoted higher dry matter accumulation through improved photosynthetic efficiency and nutrient-use efficiency (28, 29). On the other hand, reduced irrigation and nitrogen levels ($0.75 \text{ ETc} + 75 \text{ kg N ha}^{-1}$) might have induced moisture stress and nutrient deficiency, limited cell division and expansion and ultimately resulting in lower biomass production (30).

Yield attributes

Yield attributes such as number of sympodial branches per plant, number of bolls per plant and boll weight were significantly influenced by lateral depth and irrigation-nitrogen fertigation levels. These parameters are closely associated with assimilate production, partitioning and overall crop growth, thereby determining the final productivity of cotton (9).

The higher number of sympodial branches per plant recorded under subsurface lateral placement at 30 ± 2 cm could be attributed to improved moisture availability in the root zone and reduced evaporative losses (26). This favourable environment likely minimised flower and boll shedding, thereby enhancing boll retention. In contrast, surface placement (0 cm) might have

resulted in moisture stress during critical reproductive stages, leading to increased shedding of squares and bolls and consequently lower boll number per plant (27).

Similarly, the number of bolls per plant was higher under optimal lateral placement due to better plant growth and canopy development, which supported greater reproductive output per plant. Enhanced leaf area and photosynthetic activity under favourable moisture conditions might have contributed to increased assimilate availability, thereby improving boll formation and retention. Under suboptimal conditions, reduced growth and higher stress levels could have limited reproductive development, resulting in bolls per plant (31).

The interactions among the treatments were significant for yield attributes except boll weight. The combination of subsurface lateral placement at 30 ± 2 cm along with $1.0 \text{ ETc} + 100 \text{ kg N ha}^{-1}$ recorded a maximum yield attribute and the same was statistically comparable with 20 ± 2 cm along with $1.0 \text{ ETc} + 100 \text{ kg N ha}^{-1}$. Overall, the improvement in yield attributes under optimal treatments can be linked to enhanced leaf area, higher dry matter production and efficient source-sink relationship, which collectively contributed to better boll formation and development (32).

Seed cotton yield

Seed cotton yield, being the cumulative outcome of growth and yield attributes, was significantly influenced by lateral depth and irrigation-nitrogen fertigation levels. The higher yield recorded under subsurface lateral placement at 30 ± 2 cm can be attributed to improved soil moisture distribution within the active root zone and reduced evaporative losses. Such favourable conditions likely enhanced root activity, nutrient uptake and overall physiological efficiency, leading to better crop growth and productivity. In contrast, surface placement of laterals (0 cm) might have resulted in rapid moisture depletion and intermittent water stress, thereby limiting assimilate production and reducing yield (33).

Irrigation-nitrogen fertigation levels also played a decisive role in determining seed cotton yield. The treatment receiving 1.0 ETc along with 100 kg N ha^{-1} ensured a continuous and adequate supply of water and nutrients, which supported higher photosynthetic activity and dry matter accumulation (34). This, in turn, facilitated efficient translocation of assimilates towards reproductive organs, improving boll formation and development. Nitrogen, as a key component of chlorophyll and enzymes, contributes significantly to metabolic processes and enhances the source capacity of the plant (35).

On the other hand, reduced irrigation and nitrogen levels ($0.75 \text{ ETc} + 75 \text{ kg N ha}^{-1}$) might have imposed both moisture stress and nutrient limitation, adversely affecting physiological processes such as photosynthesis and assimilate partitioning (8). This could have resulted in a lower number of bolls and ultimately led to lower seed cotton yield.

The interactions among the treatments were significant for seed cotton yield. The combination of subsurface lateral placement at 30 ± 2 cm along with $1.0 \text{ ETc} + 100 \text{ kg N ha}^{-1}$ recorded the highest seed cotton yield and was statistically comparable with subsurface lateral placement at 20 ± 2 cm along with $1.0 \text{ ETc} + 100 \text{ kg N ha}^{-1}$. Compared with the treatment receiving surface lateral placement (0 cm) in combination with 0.75 ETc and 75 kg N ha^{-1} , the treatment comprising subsurface lateral placement at 30 ± 2 cm with 1.0 ETc and 100 kg N ha^{-1} increased seed cotton yield by 39.5 % during the

summer season and 47.3 % during the winter season. The successful outcome of the above treatments could be attributed to greater contribution to yield attributes, resulting from a better crop environment characterised by a continuous supply of nutrients and moisture to the crop (32).

Correlation analysis

Correlation analysis revealed a strong and positive association among plant growth, physiological traits, DMP and yield attributes across both summer and winter seasons, indicating that improvements in vegetative growth contributed substantially to yield enhancement in HDPS cotton. During the summer season, seed cotton yield exhibited strong positive correlations with plant height at 60 DAS ($r = 0.93$), LAI at 30 DAS ($r = 0.96$), LAI at 90 DAS ($r = 0.93$), LAI at harvest ($r = 0.99$), DMP at 60 DAS ($r = 0.90$), boll population ($r = 0.85$) and boll weight ($r = 0.78$), suggesting that sustained canopy development and biomass accumulation played a vital role in yield realisation. Similarly, significant positive interrelationships were observed among plant height, LAI, DMP, sympodial branches and boll population ($r = 0.82$ – 0.99), indicating coordinated crop growth and reproductive development.

In the winter season, even stronger correlations were observed, with seed cotton yield showing very high positive associations with plant height at different growth stages ($r = 0.95$ – 0.98), LAI at 30 DAS, 90 DAS and harvest ($r = 0.97$ – 0.99), DMP at various stages ($r = 0.90$ – 0.97), sympodial branches ($r = 0.93$) and boll population ($r = 0.98$). The stronger correlations during winter suggest more favourable environmental conditions for efficient conversion of vegetative growth into reproductive biomass and yield. Across both seasons, boll weight exhibited comparatively weaker associations with most growth parameters, particularly during winter ($r = 0.03$ – 0.62), indicating that boll weight was less responsive to irrigation and nitrogen management than other yield-contributing traits. Overall, the correlation matrix demonstrates that enhanced plant height, leaf area development, DMP, sympodial branching and boll production are the principal determinants of higher seed cotton yield under varying subsurface drip irrigation lateral placements and irrigation–nitrogen fertigation regimes (Fig. 4 and 5).

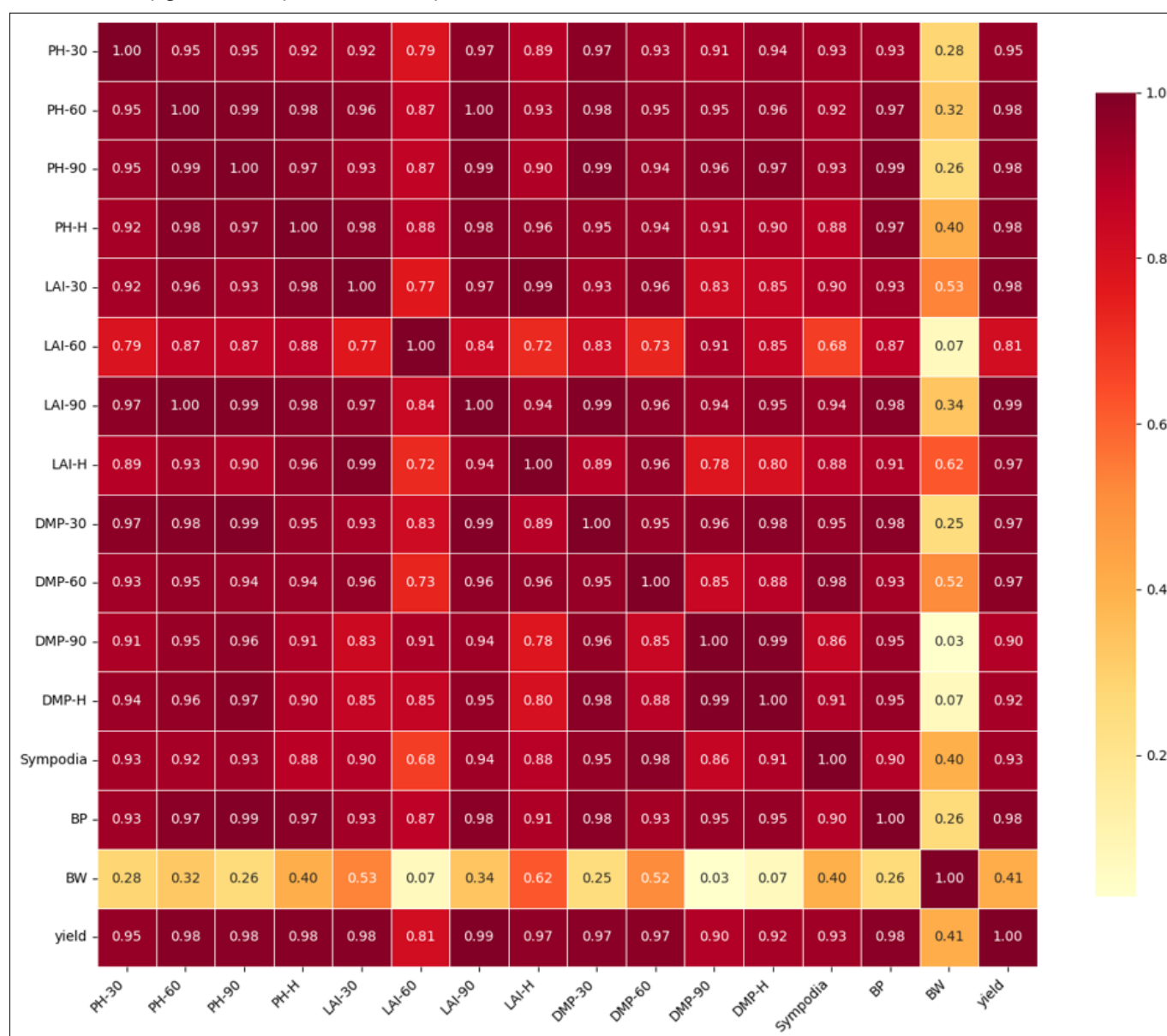


Fig. 4. Correlation matrix of growth, yield attributes and seed cotton yield summer (SI).

PH: plant height; LAI: leaf area index; Sympodia: sympodial branches per plant; BP: number of bolls per plant; BW: boll weight; Yield: seed cotton yield; DMP: dry matter production.

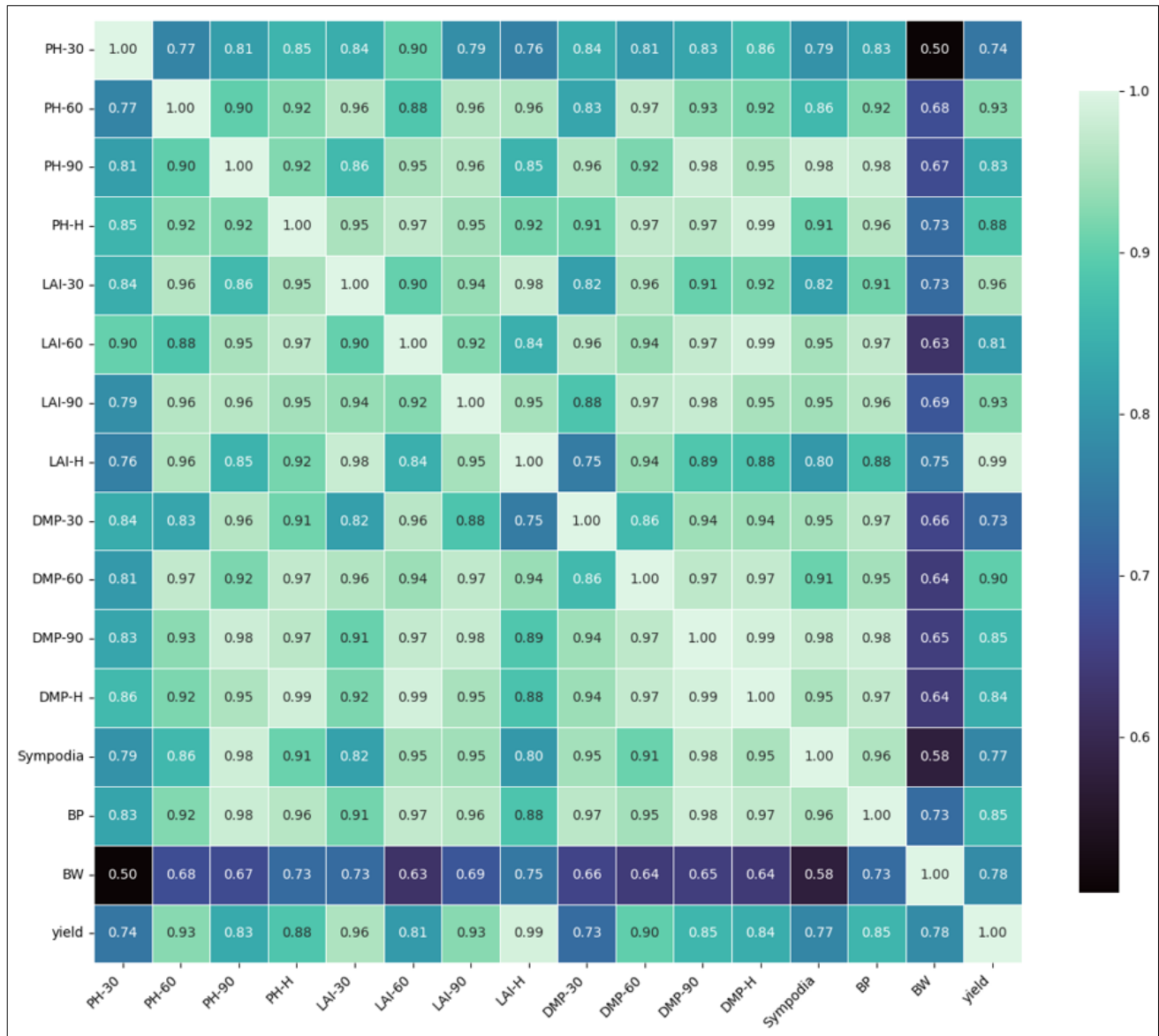


Fig. 5. Correlation Matrix of Growth, Yield Attributes and Seed Cotton Yield *winter* (Season II).

Conclusion

The results of the present investigation clearly demonstrate that subsurface drip irrigation with lateral placement at 30 ± 2 cm depth significantly improved crop growth, yield attributes and seed cotton yield under a high-density planting system. The enhanced performance under this treatment may be attributed to reduced evaporation losses improved soil moisture availability within the root zone and efficient nutrient uptake. Among the irrigation and nitrogen fertigation levels, application of irrigation at 1.0 crop evapotranspiration (ETc) and 0.75 ETc each combined with 100 kg N ha^{-1} , resulted in superior growth and yield performance, likely due to the continuous supply of water and nutrients that supported better physiological activity and assimilate partitioning. Therefore, the combination of subsurface lateral placement at 30 ± 2 cm with irrigation scheduled at 0.75 ETc and nitrogen fertigation at 100 kg N ha^{-1} can be recommended as an efficient strategy for enhancing cotton productivity under HDPS conditions, while achieving substantial water savings, particularly in drought-prone conditions. Future research should focus on validating the optimum lateral depth and fertigation schedule under different soil types, climatic conditions and cotton cultivars, as well as assessing their long-term effects on water and nutrient use efficiency.

Acknowledgements

The authors thank Tamil Nadu Agricultural University, Coimbatore, for providing the research facilities required to conduct the experiments.

Authors' contributions

MS conducted the experiment, recorded and analysed the data. SS supervised the study, designed the experiment and contributed to data analysis and manuscript revision. MR, PA, SBR and TR provided guidance during the experiment and assisted with manuscript revision. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT for grammar correction and language refinement. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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