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RESEARCH ARTICLE

Interaction of compact varieties, nitrogen levels and deficit sub-surface drip irrigation on growth and yield of cotton under high-density planting system

Manibharathi S[1], Somasundaram S[2*], Parasuraman P[3], Subramanian A[4], Ravichandran V[5] & Manikanda Boopathi N[6]

[1]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Cotton Research Station, Tamil Nadu Agricultural University, Veppanthattai, Perambalur 621 116, Tamil Nadu, India
[3]Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Department of Cotton, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[5]Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[6]Department of Plant Biotechnology, Centre for Plant Molecular Biology and Biotechnology, Tamil Nadu Agricultural University,Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - somasundaram.s@tnau.ac.in

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Abstract

A field experiment was conducted during the 2024-25 summer and winter seasons at Wetland Farm, TNAU, Coimbatore, to optimize irrigation and nitrogen management for cotton under high-density planting systems (HDPS) in semi-arid tropics. The trial, designed as a split-split plot with three irrigation levels in the main plots (1.0, 0.8 and 0.6 ETc), two varieties in the sub-plots (CO 17, VPT 2) and three nitrogen management strategies in the sub-sub plots (Control, 100 % RDN through granular urea, 50 % RDN through granular urea + 20 % N through Nano urea @ 25 DAS + 20 % N through Nano urea @ 45 DAS + 10 % N through Nano urea @ 65 DAS), each replicated three times. Results revealed that the 1.0 ETc irrigation regime significantly enhanced plant height, bolls per plant and seed cotton yield. Compact variety CO 17 showed superior performance in growth and yield under a high-density planting system compared to VPT 2. Regarding nitrogen management, application of 50 % RDN through granular urea + 20 % N through Nano urea @ 25 DAS + 20 % N through Nano urea @ 45 DAS + 10 % N through Nano urea @ 65 DAS significantly increased the seed cotton yield. For high-density cotton cultivation in semi-arid regions, the CO 17 variety under 1.0 ETc sub-surface drip irrigation, combined with the nitrogen strategy, is recommended to maximize productivity and profitability. This approach offers a sustainable framework for improving cotton yields in water and nutrient-constrained environments.

Keywords: compact varieties; ETc; HDPS; nitrogen; sub-surface drip irrigation; yield

Introduction

Cotton (*Gossypium hirsutum* L.), also known as "White Gold," is one of the most important commercial cash crops. It is cultivated across diverse agro-climatic zones, predominantly in the semi-arid regions of India. In India, cotton was cultivated in 129 lakh hectares, with a total production of 336 lakh bales and with an average productivity of 443 kg ha^{-1} during 2022-23, whereas in Tamil Nadu, during 2022-23, cotton was cultivated in 1.73 lakh hectares, with a total production of 3.19 lakh bales and with an average productivity of 313 kg ha^{-1} (1).

For arid and semi-arid regions, irrigation in agriculture accounts for a significant portion of freshwater consumption (2). Agricultural sectors in these regions are facing challenges due to increased water demands combined with growing populations, insufficient water resources and climate change-induced rainfall variability (3). To reduce water consumption in agriculture, drip irrigation technologies are effective. Deficit irrigation is a sustainable approach that enhances the effectiveness of irrigation water utilization. Deficit irrigation aims to maintain soil moisture at levels that support yields without over-saturating the soil profile (4).

Cotton generally requires approximately 600 mm of water during its growth period. The conventional irrigation method in cotton leads to enormous losses of water through evaporation, seepage and deep percolation, which leads to the development of salinity, water logging and leaching of nutrients in the field. Conventional cotton irrigation methods are described as wasteful and produce considerable run-off and leaching of water and pollutants (5). The lower yields of cotton could be attributed to inefficient irrigation and fertilizer (nitrogen) management practices (6).

Cotton yield is highly sensitive to weather, soil, irrigation and crop management practices, with irrigation and nitrogen levels as critical limiting factors for growth and yield (7). Efficient irrigation methods, such as regulated deficit irrigation, can significantly reduce runoff from crop fields while supporting optimal plant development. Nitrogen, a vital nutrient for cotton, promotes photosynthesis, canopy development and reproductive growth when applied at an optimal rate, which varies by growth pattern and is essential for maximizing yield (8, 9). Synchronizing crop demand with nitrogen application plays an indispensable role in plant photosynthesis and biomass accumulation, canopy development and reproductive growth (10). Nitrogen is one of the decisive as well as expensive inputs which is applied to increase crop production. The application of nano nitrogen in cotton cultivation has shown promising results in enhancing growth, yield and nutrient uptake. Recent advances in nano nitrogen technology, such as Nano urea, have demonstrated potential to enhance growth, yield and nitrogen use efficiency, reducing the need for conventional nitrogen fertilizers (11).

The concept of deficit irrigation practices for cotton was first introduced in the 1970s (12). Effectively implementing deficit irrigation techniques can significantly reduce water usage and crops such as cotton are suitable for deficit irrigation, whether applied consistently during the entire growth period or at specific stages of development (13). Cotton is well-suited for deficit irrigation, whether applied throughout its growth cycle or at specific developmental stages. Sub-surface drip irrigation (SSDI) is particularly effective under water limiting conditions, helping to reduce runoff and minimize contamination of downstream water bodies when compared to traditional furrow irrigation (14, 15). Sub-surface drip irrigation and nitrogen management are technologies that improve both water and nitrogen use efficiency to a great extent.

Subsurface drip irrigation (SSDI) enhances water efficiency by delivering water directly to the root zone through buried laterals with regularly spaced drippers, minimizing surface runoff and evaporation compared to surface drip and flood irrigation (16, 17).

Increasing planting density alone does not ensure higher yields in cotton cultivation. To achieve optimal productivity, it must be paired with advanced cultivation techniques and the selection of suitable cultivars. Choosing cultivars with disease resistance, early maturity and high yield potential is critical for optimizing outcomes in high-density planting systems, particularly when paired with efficient irrigation methods like subsurface drip irrigation (SSDI) and deficit irrigation. These irrigation strategies conserve water and enhance nutrient delivery, complementing the benefits of well-selected cultivars. Integrating effective management practices with appropriate cultivar selection ensures maximum yield potential in densely planted cotton fields under water-limited conditions (18).

Thus, the SSDI technique can be exploited to realize more crops per drop of water without sacrificing the seed cotton yield, besides sustaining cotton productivity. So far, the feasibility of SSDI in cotton agro-ecosystems has been less evaluated in India and the present study offers an opportunity to fill this gap in the extant agricultural scenario. We hypothesize that SSDI would improve cotton productivity and save a significant amount of water prevalent in India.

The present investigation implements an experimental approach to explore this enunciated research query and produce data-based information for its implementation on a large scale under semi-arid climates. Specifically, the study aims to assess the effects of SSDI and nitrogen management on growth, yield attributes and final yield under high-density planting systems (HDPS), using three ETc-based deficit irrigation levels, three nitrogen strategies and two compact cotton varieties.

Materials and Methods

Experimentation details

The field experiments were conducted in Field No. N3 at the Wetland Farm, Department of Agronomy, Tamil Nadu Agricultural University, Coimbatore (11° 07′ N latitude and 77° 32′ E longitude at an altitude of 426.7 m above the mean sea level) during the summer and winter seasons of 2024-25. In the local context, summer spans from March to May, characterized by high temperatures and dry conditions, while winter extends from November to February, featuring cooler temperatures and occasional rainfall. The site falls under the Tamil Nadu Western Agro-Climatic zone. A split-split plot design was employed with three replications, comprising the following factors:

Main plots - irrigation regimes

- I1: 1.0 ETc (100 % crop evapotranspiration)
- I2: 0.8 ETc (80 % crop evapotranspiration)
- I3: 0.6 ETc (60 % crop evapotranspiration)

Sub-plots - varieties

- V1: CO 17
- V2: VPT 2

Sub-sub plots - nitrogen management strategies

- N1: Control
- N2: 100 % RDN through granular urea
- N3: 50 % RDN through granular urea + 20 % N through Nano urea at 25 DAS + 20 % N through Nano urea at 45 DAS + 10 % N through Nano urea at 65 DAS

Irrigation scheduling

Applied irrigation was determined daily using class A pan evaporation data, pan coefficient and appropriate crop coefficient values at different stages. The daily pan evaporation data were collected from the Agro Climatic Research Centre, Tamil Nadu Agricultural University, Coimbatore.

$$ETc = Kc \times ETo \quad \text{(Eqn. 1)}$$
$$ETo = Kp \times Epan \quad \text{(Eqn. 2)}$$
$$ETc = Kc \times Kp \times Epan \quad \text{(Eqn. 3)}$$

Where,

ETc = Crop evapotranspiration (mm day^{1})

ETo = Reference evapotranspiration

Epan = Pan evaporation (mm day^{1})

Kp = Pan coefficient (0.8)

Kc = Crop coefficient.

The crop coefficient (Kc) value of cotton (19) is mentioned in Table 1.

Data collection

Growth and yield parameters were recorded by randomly selecting and labelling ten plants in each experimental plot. The following growth and yield parameters were measured: plant height, number of monopodial branches per plant, no. of bolls per plant, no. of bolls per m^2, boll weight and seed cotton yield. Harvested bolls were air-dried to achieve a moisture content below 11 % and the average boll weight was calculated. The average boll weight per boll is calculated by dividing the total weight of a sample of individual bolls by the number of bolls in that sample. Seed cotton was picked from the plot and the yield was converted into kg ha^{-1}. The collected data were subjected to statistical analysis of variance (ANOVA). Mean square errors were subjected to the least significant difference (LSD) test at the 5 % probability level to identify statistically significant differences between treatment (20).

Table 1. Kc value of cotton (FAO-56 Paper)

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

Results

Plant height (cm)

A significant difference in plant height was observed by deficit irrigation, compact varieties and nitrogen management during both the seasons (Table 2).

Plants under 1.0 ETc deficit irrigation were significantly taller at all growth stages (30.9 cm at 30 DAS, 58 cm at 60 DAS and 83.5 cm at 90 DAS) and attained the maximum plant height of 103.4 cm at harvest and followed by 0.8 ETc with a plant height of 95.6 cm at harvest during the summer season. During winter, Plants under 1.0 ETc were significantly taller at all the growth stages (31.4 cm at 30 DAS, 61.9 cm at 60 DAS and 86.3 cm at 90 DAS) and attained the maximum plant height of 105.5 cm at harvest and was followed by 0.8 ETc with a plant height of 97.2 cm at harvest. Shorter plants were observed with 0.6 ETc, which recorded a plant height of 86.5 cm and 88.2 cm at harvest during the summer and winter seasons respectively.

For compact varieties, a significant difference in plant height was registered from 60 DAS to harvest during both seasons. The compact variety CO 17 was significantly recorded taller plants with a height of 97.6 cm and 99.3 cm at harvest, whereas VPT 2 produced shorter plants with a height of 92.8 cm and 94.7 cm at harvest during summer and winter seasons respectively.

Table 2. Effect of varieties, nitrogen and deficit sub-surface drip irrigation on plant height of cotton under high-density planting system

Treatments	30 DAS		60 DAS		90 DAS		At Harvest	
	S I	S II	S I	S II	S I	S II	S I	S II
Deficit irrigation								
I1	30.9a	31.4	58.0	61.9	83.5	86.3	103.4	105.5
I2	29.9b	30.4	53.8	57.4	77.4	79.7	95.6	97.2
I3	28.5c	29.3	46.5	49.9	69.8	71.1	86.5	88.2
SEd	0.25	0.25	0.45	0.48	0.67	0.69	0.87	0.88
CD (p = 0.05)	0.69	0.71	1.27	1.35	1.87	1.93	2.43	2.45
Varieties								
V1	30.0a	30.6	54.1a	57.7	78.5	81.1	97.6	99.3
V2	29.5b	30.2	51.4b	55.1	75.3	77.0	92.8	94.7
SEd	0.46	0.47	0.78	0.84	1.16	1.19	1.38	1.41
CD (p = 0.05)	NS	NS	1.93	2.06	2.85	2.91	3.39	3.46
Nitrogen management								
N1	29.3	29.8	48.7	52.4	71.3	73.6	82.1	84.4
N2	29.8	30.4	54.1a	57.7a	78.8a	80.7a	99.8a	101.2a
N3	30.2	30.9	55.6a	59.1a	80.6a	82.9a	103.6a	105.4a
SEd	0.66	0.67	1.19	1.28	1.74	1.79	2.17	2.21
CD (p = 0.05)	NS	NS	2.47	2.64	3.60	3.70	4.48	4.57
Irrigation × varieties								
SEd	0.62	0.63	1.07	1.14	1.58	1.61	1.91	1.94
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Varieties × nitrogen								
SEd	0.89	0.91	1.59	1.70	2.33	2.39	2.86	2.92
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation × nitrogen								
SEd	0.97	0.99	1.75	1.87	2.56	2.63	3.19	3.25
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation × varieties × nitrogen								
SEd	1.44	1.47	2.58	2.76	3.77	3.87	4.66	4.75
CD (p = 0.05)	NS	NS	NS	NS	NS	NS	NS	NS

For nitrogen management, a significant difference in plant height was registered from 60 DAS to harvest during both seasons. The application of 50 % RDN through granular urea + split Nano urea treatment @ 25, 45 and 65 DAS significantly produced taller plants with a height of 103.6 cm and 105.4 cm at harvest and was comparable with the application of 100 % RDN through granular urea which produced plant height of 99.8 cm and 101.2 cm at harvest during summer and winter seasons respectively. The control treatment without nitrogen produced shorter plant height of 82.1 cm and 84.4 cm at harvest during summer and winter seasons respectively.

No significant differences were found among the interaction of deficit irrigation × compact varieties, deficit irrigation × nitrogen management, compact varieties × nitrogen management and deficit irrigation × compact varieties × nitrogen management. Compact varieties in the range of 99-105 cm are suitable for mechanical harvesting.

Number of monopodial branches per plant

The number of monopodial branches per plant was not significantly influenced by deficit irrigation, compact varieties and nitrogen management during both seasons and their interaction effects were also non-significant (Table 3).

Number of bolls per plant

Significant differences in number bolls plant^{-1} were observed with deficit irrigation, compact varieties and nitrogen management during the summer and winter seasons respectively (Table 4).

Table 3. Effect of varieties, nitrogen and deficit sub-surface drip irrigation on number of monopodial branches per plant of cotton under high-density planting system

Number of monopodial branches per plant		
Treatments	**S I (Summer)**	**S II (Winter)**
Deficit irrigation		
I1	0.69	0.81
I2	0.69	0.81
I3	0.68	0.80
SEd	0.005	0.006
CD (p = 0.05)	NS	NS
Varieties		
V1	0.69	0.81
V2	0.68	0.80
SEd	0.01	0.01
CD (p = 0.05)	NS	NS
Nitrogen management		
N1	0.68	0.80
N2	0.69	0.81
N3	0.69	0.81
SEd	0.01	0.01
CD (p = 0.05)	NS	NS
Irrigation × varieties		
SEd	0.01	0.01
CD (p = 0.05)	NS	NS
Varieties × nitrogen		
SEd	0.02	0.02
CD (p = 0.05)	NS	NS
Irrigation × nitrogen		
SEd	0.02	0.02
CD (p = 0.05)	NS	NS
Irrigation × varieties × nitrogen		
SEd	0.03	0.03
CD (p = 0.05)	NS	NS

Among the deficit irrigation, significant differences in number of bolls plant^{-1} were observed during both the seasons. Deficit irrigation with 1.0 ETc significantly registered a higher number of bolls with 13.6 and 12.6 bolls plant^{-1} and this was followed by 0.8 ETc (12.6 and 10.7 bolls plant^{-1}) during both the seasons. Deficit irrigation with 0.8 ETc recorded a lower number of bolls with 10.6 and 9.3 bolls plant^{-1} during summer and winter seasons, respectively.

Regarding compact varieties, significant differences in bolls plant^{-1} were observed during both seasons. The compact variety CO 17 significantly recorded a higher number of bolls plant^{-1} (12.9 and 12.5), whereas VPT 2 produced a lower number of bolls with 11.7 bolls plant^{-1} in summer and 11.9 bolls plant^{-1} in winter seasons, respectively.

Regarding nitrogen management, significant differences in bolls plant^{-1} were observed during both seasons. Application of 50 % RDN through granular urea + 20 % N through Nano urea @ 25 DAS + 20 % N through Nano urea @ 45 DAS + 10 % N through Nano urea @ 65 DAS significantly produced higher number of bolls with 14.7 bolls plant^{-1} in summer and 13.8 bolls plant^{-1} in winter. This was comparable with the application of 100 % RDN through granular urea with 14.1 bolls plant^{-1} in summer and was followed by the same in winter with 12.7 bolls plant^{-1}. The lower number of bolls with 8.0 bolls plant^{-1} in summer, 5.7 bolls plant^{-1} in winter seasons respectively, were recorded in control.

The interaction between deficit irrigation and compact varieties was significant. Deficit irrigation 1.0 ETc with CO 17 significantly produced more bolls (13.8 and 12.5 bolls plant^{-1}) and was comparable with 1.0 ETc with VPT 2 (13.4 and 11.9 bolls plant^{-1}) during both the seasons. 0.6 ETc with VPT 2 recorded a lower number of bolls (9.3 and 8.1 bolls plant^{-1}) and

Table 4. Effect of varieties, nitrogen and deficit sub-surface drip irrigation on number of bolls plant and per m^2 of cotton under high-density planting system

Treatments	Number of bolls per plant		Number of bolls per m^2	
	S I (Summer)	**S II (Winter)**	**S I (Summer)**	**S II (Winter)**
Deficit irrigation				
I1	13.6	12.6	101.4	91.3
I2	12.6	10.7	93.8	79.9
I3	10.6	9.3	79.1	69.4
SEd	0.13	0.12	0.98	0.95
CD (p = 0.05)	0.36	0.35	2.72	2.64
Varieties				
V1	12.9	12.5	95.8	84.3
V2	11.7	11.9	87.0	76.0
SEd	0.17	0.14	1.28	1.10
CD (p = 0.05)	0.42	0.36	3.13	2.69
Nitrogen management				
N1	8.0	5.7	59.8	42.5
N2	14.1	12.7	105.3	95.2
N3	14.7	13.8	109.3	102.8
SEd	0.29	0.26	2.17	1.98
CD (p = 0.05)	0.60	0.54	4.48	4.09
Irrigation × varieties				
I1 x V1	13.8	12.5	103.0	93.6
I1 x V2	13.4	11.9	99.9	89.0
I2 x V1	12.9	10.9	95.7	81.5
I2 x V2	12.3	10.5	92.0	78.3
I3 x V1	11.9	10.4	88.9	77.9
I3 x V2	9.3	8.1	69.3	60.8
SEd	0.24	0.22	1.85	1.65
CD (p=0.05)	0.63	0.56	4.70	4.21
Varieties × nitrogen				
SEd	0.37	0.34	2.81	2.53
CD (p=0.05)	NS	NS	NS	NS
Irrigation × nitrogen				
I1 x N1	8.8	7.3	65.7	54.7
I1 x N2	15.7	14.3	116.6	106.5
I1 x N3	16.4	15.1	122.0	112.6
I2 x N1	08.1	5.2	60.5	38.7
I2 x N2	14.8	13.3	110.1	99.6
I2 x N3	14.9	13.6	110.8	101.5
I3 x N1	7.1	4.6	53.1	34.2
I3 x N2	12.0	10.7	89.1	79.7
I3 x N3	12.8	12.6	95.1	94.2
SEd	0.43	0.39	3.22	2.95
CD (p=0.05)	0.92	0.84	8.86	6.32
Irrigation × varieties × nitrogen				
I1 × V1 × N1	8.9	7.6	66.1	56.6
I1 × V1 × N2	15.8	14.5	117.3	108.0
I1 × V1 × N3	16.9	15.6	125.5	116.2
I1 × V2 × N1	8.8	7.1	65.3	52.8
I1 × V2 × N2	15.6	14.1	115.9	105.0
I1 × V2 × N3	16.0	14.6	118.4	109.1
I2 × V1 × N1	8.5	5.4	63.1	40.2
I2 × V1 × N2	15.4	14.0	114.4	104.3
I2 × V1 × N3	14.8	13.4	109.5	100.2
I2 × V2 × N1	7.8	5.0	57.9	37.2
I2 × V2 × N2	14.2	12.7	105.8	94.9
I2 × V2 × N3	15.1	13.8	112.1	102.8
I3 × V1 × N1	7.4	4.7	54.9	35.0
I3 × V1 × N2	13.8	12.0	102.5	89.4
I3 × V1 × N3	14.7	14.7	109.2	109.5
I3 × V2 × N1	6.9	4.5	51.2	33.5
I3 × V2 × N2	10.2	9.4	75.7	70.0
I3 × V2 × N3	10.9	10.6	80.9	78.9
Sed	0.62	0.56	4.61	4.18
CD (p = 0.05)	1.31	1.18	9.73	8.80

the interaction between compact varieties and nitrogen management was non-significant during both seasons.

The interaction between deficit irrigation and nitrogen management was significant during both seasons. The highest boll count was observed under 1.0 ETc + split Nano urea treatment (16.4 and 15.1 bolls per plant in both seasons) and was comparable with 1.0 ETc along with application of 100 % RDN through granular urea which produced 15.7 bolls plant^{-1} in summer and 14.3 bolls plant^{-1} in winter respectively. The lower number of bolls with 7.1 bolls plant^{-1} in summer, 4.6 bolls plant^{-1} in winter respectively, were recorded in 0.6 ETc with no nitrogen application (control).

In a three-way interaction, deficit irrigation at 1.0 ETc with CO 17 along with split Nano urea treatment recorded 16.9 bolls plant^{-1} in summer and 15.6 bolls plant^{-1} in winter, comparable to VPT 2 (16 bolls plant^{-1} in summer) under similar conditions.

Similarly, 1.0 ETc with CO 17 and 100 % RDN through granular urea recorded 15.8 bolls plant^{-1} in summer and 14.5 bolls plant^{-1} in winter, comparable to VPT 2 (15.6 bolls plant^{-1} in summer and 14.1 bolls plant^{-1} in winter) during both seasons. In contrast, the control treatment with 0.6 ETc and VPT 2 produced significantly fewer bolls, yielding 6.9 bolls plant^{-1} in summer and 4.5 bolls plant^{-1} in winter during both seasons.

Number of bolls per m^2

Significant differences were recorded in number of bolls m^{-2} with respect to deficit irrigation, compact varieties and nitrogen management during the summer and winter seasons respectively (Table 4).

Deficit irrigation at 1.0 ETc significantly increased boll numbers to 101.4 and 91.3 bolls m^{-2} and was followed by 0.8 ETc (93.8 and 79.9 bolls m^{-2}) during both the seasons. Deficit irrigation with 0.6 ETc recorded a lower number of bolls with 79.1 and 69.4 bolls m^{-2} during summer and winter, respectively.

Regarding compact varieties, CO 17 significantly recorded a higher number of bolls m^{-2} (95.8 and 84.3) and whereas VPT 2 produced a lower number of bolls, recording 87.0 bolls m^{-2} in summer and 76.0 bolls m^{-2} in winter, respectively.

Regarding nitrogen management, significant differences in bolls m^{-2} was observed during both the seasons. Application of 50 % RDN through granular urea + split Nano urea treatment (N_3) produced higher number of bolls with 109.3 bolls m^{-2} in summer and 102.8 bolls m^{-2} in winter and was comparable with application of 100 % RDN through granular urea with 105.3 bolls m^{-2} in summer and followed by the same with 95.2 bolls m^{-2} in winter respectively. The lower number of bolls with 59.8 bolls m^{-2} in summer and 42.5 bolls m^{-2} in winter was recorded by the control (without the application of nitrogen).

The interaction between deficit irrigation and compact varieties was significant. Deficit irrigation 1.0 ETc with CO 17 significantly produced more bolls (103 and 93.6 bolls m^{-2} in summer and winter, respectively) and was comparable to 1.0 ETc with VPT 2 in summer (99.9 bolls m^{-2}), followed by its performance in winter (89 bolls m^{-2}). Deficit irrigation 0.6 ETc with VPT 2 recorded a significantly lower number of bolls (69.3 and 60.8 bolls m^{-2}) during both the seasons.

The interaction between compact varieties and nitrogen management was non-significant during both seasons.

The interaction between deficit irrigation and nitrogen management showed significant differences during both the seasons. Deficit irrigation 1.0 ETc along with the application of 50 % RDN through granular urea + split Nano urea treatment produced a higher number of bolls with 122.0 bolls m^{-2} in summer and 112.6 bolls m^{-2} in winter and was comparable with 1.0 ETc along with the application of 100 % RDN through granular urea with (116.6 bolls m^{-2} in summer and 106.5 bolls m^{-2} in winter). The lower number of bolls with 53.1 bolls m^{-2} in summer and 34.2 bolls m^{-2} in winter respectively was recorded by 0.6 ETc under control without application of nitrogen.

In three-way interaction, deficit irrigation 1.0 ETc with CO 17 along with the application of 50 % RDN through granular urea + split Nano urea treatment ($I_1V_1N_3$) recorded higher number of bolls (125.5 and 116.2 bolls m^{-2}) during both the seasons and was comparable with I1V2N3 produced 118.4 bolls m^{-2} in summer, regarding winter I3V1N3 recorded in 109.5 bolls m^{-2}.

A similar trend was recorded under I1V2N3, I1V2N2, I1V1N3 and I1V1N2 in summer and I1V2N3, I1V1N3 and I1V1N2 in winter. Whereas deficit irrigation 0.6 ETc with VPT 2 in control treatment produced lower number of bolls (51.2 and 33.5 bolls m^{-2}) during both the seasons.

Boll weight (g)

Significant differences in boll weight were observed due to deficit irrigation and nitrogen management during the summer and winter seasons, respectively. Deficit irrigation of 1.0 ETc significantly registered a higher boll weight with 4.1 and 4.0 g, followed by 0.8 ETc (3.9 g) during both the seasons. Deficit irrigation with 0.6 ETc recorded a lower boll weight (3.8 g) in both the seasons (Table 5).

Application of 50 % RDN through granular urea + split Nano urea treatment significantly produced higher boll weight with 4.1 g in summer and 4.0 g in winter and was followed by application of 100 % RDN through granular urea (3.9 g) in summer and comparable with the same (3.9 g) in winter respectively. The lowest boll weight with 3.7 g in summer and 3.7 g in winter respectively, was recorded in control with no application of nitrogen. No interaction effect was observed.

Seed cotton yield (kg ha^{-1})

Significant difference in seed cotton yield was observed with deficit irrigation, compact varieties and nitrogen management during both the seasons respectively (Table 6).

Deficit irrigation 1.0 ETc recorded the higher seed cotton yield of 2347 kg ha^{-1} in summer and 2255 kg ha^{-1} in winter respectively and was followed by deficit irrigation 0.8 ETc (2131 and 2036 kg ha^{-1}) during both the seasons. 0.6 ETc recorded lower seed cotton yield of 1909 kg ha^{-1} in summer and 1822 kg ha^{-1} in winter season respectively.

Table 5. Effect of varieties, nitrogen and deficit sub-surface drip irrigation on boll weight of cotton under high-density planting system

Treatments	Boll weight (g)	
	S I (Summer)	S II (Winter)
Deficit irrigation		
I1	4.1	4.0
I2	3.9	3.9
I3	3.8	3.8
SEd	0.03	0.03
CD (p = 0.05)	0.09	0.09
Varieties		
V1	3.9	3.9
V2	3.9	3.9
SEd	0.06	0.06
CD (p = 0.05)	NS	NS
Nitrogen management		
N1	3.7	3.7
N2	3.9	3.9
N3	4.14	4.0
SEd	0.08	0.08
CD (p = 0.05)	0.18	0.18
Irrigation × varieties		
SEd	0.08	0.08
CD (p = 0.05)	NS	NS
Varieties × nitrogen		
SEd	0.11	0.11
CD (p = 0.05)	NS	NS
Irrigation × nitrogen		
SEd	0.13	0.12
CD (p = 0.05)	NS	NS
Irrigation × varieties × nitrogen		
SEd	0.21	0.21
CD (p = 0.05)	NS	NS

Compact variety CO 17 recorded higher seed cotton yield of 2185 kg ha^{-1} in summer season and 2093 kg ha^{-1} in winter season respectively. VPT 2 recorded lower seed cotton yield of 2073 kg ha^{-1} in summer and 1983 kg ha^{-1} in winter season respectively.

Regarding nitrogen management, application of 50 % RDN through granular urea + split Nano urea treatment recorded higher seed cotton yield of 2375 kg ha^{-1} in summer season and 2283 kg ha^{-1} in winter season and was followed by application of 100 % RDN through granular urea which recorded 2177 and 2087 kg ha^{-1} during summer and winter seasons respectively. Lower seed cotton yield was recorded by control with 1835 kg ha^{-1} in summer season and 1744 kg ha^{-1}in winter season respectively.

There is no significant interaction with deficit irrigation and compact varieties for seed cotton yield in during both the seasons.

Compact variety CO 17 along with application of 50 % RDN through granular urea + split Nano urea treatment recorded higher seed cotton yield of 2399 kg ha^{-1} in summer season and 2306 kg ha^{-1} in winter season respectively and was comparable with CO 17 along with application of 100 % RDN through granular urea was recorded (2342 and 2249 kg ha^{-1}) during both the seasons and was followed by VPT 2 along with application of 50 % RDN through granular urea + split Nano urea treatment recorded a seed cotton yield of 2350 kg ha^{-1} in summer and 2259 kg ha^{-1} in winter respectively this was followed by VPT 2 along with application of 100 % RDN through granular urea (2013 and 1924 kg ha^{-1}) during both the seasons. Lower seed cotton yield was recorded by CO 17 under control (1815 and 1722 kg ha^{-1}) during both the seasons.

Table 6. Effect of varieties, nitrogen and deficit sub-surface drip irrigation on seed cotton yield of cotton under high-density planting system

Seed cotton yield (kg ha^{-1})		
Treatments	**S I (Summer)**	**S II (Winter)**
Deficit irrigation		
I1	2347	2255
I2	2131	2036
I3	1909	1822
SEd	21	20
CD (p = 0.05)	60	58
Varieties		
V1	2185	2093
V2	2073	1983
SEd	31	29
CD (p = 0.05)	76	72
Nitrogen management		
N1	1835	1744
N2	2177	2087
N3	2375	2283
SEd	49	47
CD (p = 0.05)	101	97
Irrigation × varieties		
SEd	43	41
CD (p = 0.05)	NS	NS
Varieties × nitrogen		
V1 × N1	1815	1722
V1 × N2	2342	2249
V1 × N3	2399	2306
V2 × N1	1856	1765
V2 × N2	2013	1924
V2 × N3	2350	2259
SEd	64	62
CD (p = 0.05)	139	133
Irrigation × nitrogen		
I1 × N1	1979	1887
I1 × N2	2442	2350
I1 × N3	2620	2528
I2 × N1	1757	1663
I2 × N2	2322	2225
I2 × N3	2316	2220
I3 × N1	1771	1682
I3 × N2	1769	1685
I3 × N3	2188	2100
Sed	72	70
CD (p = 0.05)	155	148
Irrigation × varieties × nitrogen		
I1 × V1 × N1	2037	1941
I1 × V1 × N2	2499	2404
I1 × V1 × N3	2679	2587
I1 × V2 × N1	1921	1833
I1 × V2 × N2	2386	2297
I1 × V2 × N3	2562	2469
I2 × V1 × N1	1816	1719
I2 × V1 × N2	2467	2371
I2 × V1 × N3	2277	2177
I2 × V2 × N1	1698	1607
I2 × V2 × N2	2177	2080
I2 × V2 × N3	2356	2263
I3 × V1 × N1	1594	1508
I3 × V1 × N2	2060	1974
I3 × V1 × N3	2243	2156
I3 × V2 × N1	1949	1857
I3 × V2 × N2	1478	1397
I3 × V2 × N3	2134	2045
SEd	105	101
CD (p = 0.05)	223	213

Deficit irrigation 1.0 ETc along with application of 50 % RDN through granular urea + split Nano urea treatment recorded higher seed cotton yield of 2620 kg ha^{-1} in summer and 2528 kg ha^{-1} in winter and was followed by 1.0 ETc along with application of 100 % RDN through granular urea (2442 and 2350 kg ha^{-1}) during both the seasons and was comparable with 0.8 ETc with the application of 100 % RDN through granular urea (2322 and 2225 kg ha^{-1}). The similar was recorded with 0.8 ETc along with application of 50 % RDN through granular urea + split Nano urea treatment recorded seed cotton yield of 2220 kg ha^{-1} in winter season only. Lower seed cotton yield was recorded (1757 and 1663 kg ha^{-1}) in 0.8 ETc under control during both the seasons.

Higher seed cotton yield was recorded by 1.0 ETc with CO 17 along with the application of 100 % RDN through granular urea + split Nano urea treatment with 2679 kg ha^{-1} in summer and 2587 kg ha^{-1} in winter season and was comparable with 1.0 ETc with VPT 2 along with application of 100 % RDN through granular urea + split Nano urea treatment with (2562 and 2469 kg ha^{-1}) during both the seasons, 1.0 ETc with CO 17 along with the application of 100 % RDN through granular urea (2499 and 2404 kg ha^{-1}) and 0.8 ETc with CO 17 along with the application of 100 % RDN through granular urea (2467 and 2371 kg ha^{-1}) during both the seasons. Lower seed cotton yield was recorded by 0.6 ETc in VPT 2 under application of 100 % RDN through granular urea (1478 and 1397 kg ha^{-1}) during both the seasons.

Discussion

Subsurface drip irrigation (SDI) is a modern and under specific conditions, the most efficient method for irrigating crops and landscapes. It has been evident that with subsurface drip irrigation, one may achieve higher production than any other irrigation method (21). These advantages stem from scientifically based design and management parameters distinguishing SDI from surface drip systems. Its efficient application is based on the soil water movement under unsaturated conditions (22) when the capillary forces prevail over gravity (23). Capillary forces decrease as the soil becomes wetter, while in dry soil, these forces are greater than gravity. This simple and fundamental concept leads to the conclusion that when using subsurface drip irrigation water should be applied in small and frequent amounts so that it moves into the soil mainly due to capillary forces.

One additional practical advantage of SDI is that it maintains a relatively dry soil surface that permits farm equipment access and movement during the whole irrigation period and significantly reduces weed growth (24). In addition, it restricts root rot and other soil diseases. It prevents crust creation that inhibits soil aeration and rainwater infiltration into the soil resulting in excessive surface runoff. Reduced surface moisture from improved soil cover limits pathogen proliferation, while enhanced soil structure prevents crusting, promoting aeration and water infiltration. On the negative side, some disadvantages can be encountered when using subsurface drip irrigation. However, SDI systems also face limitations, including difficulty in inspection of a subsurface system, emitters clogging by roots and solids may cause poor system performance; a subsurface system is difficult to repair and maintain (25).

Higher growth and yield parameters in subsurface drip irrigation may be attributed to higher moisture content in subsurface drip irrigation during all stages at 15 cm depth over surface drip irrigation. Growth and yield increase under SDI are primarily due to higher soil moisture during critical stages such as flowering and boll formation. This might be due to the release of water strictly in the root zone drop by drop in the right quantity, maintaining soil: air ratio at an optimum level for plant growth and development and due to less evaporation, percolation and leaching losses which ultimately leads to maintenance of favourable soil moisture percent. This situation increased the soil moisture percent throughout the growing season which ultimately resulted in higher growth and development of plants, similar findings were also observed previously (26).

Growth attributes

The sub-surface drip irrigation, 1.0 ETc irrigation regime creates a favourable environment at the root rhizosphere for increasing soil moisture and nutrient absorption which leads to an increase the cell elongation and multiplication. An optimum supply of moisture and nutrients also results in maximum photosynthetic rate and stomatal conductance, which is ultimately reflected in healthy and vigorous plant growth (10). In deficit irrigation, the inadequate availability of irrigation water at all the crop growth stages forced the crop to remain at moisture-stress conditions. The continuous stress situation decreases the enzymatic activities as well as all the physiological processes, finally reflecting adverse effects on the growth attributes of the cotton.

All the growth attributes are significantly influenced by different subsurface drip irrigation and nitrogen management at different growth stages of the crop.

Plant height

Plant height is an important morphological character that provides sites for nodes and internodes from where sympodial branches emerge and thus plays an important role in determining the morphological framework relating to productivity (27). In general, the early growth of cotton is very slow compared to other field crops.

Plant growth is the reflection of the utilization of the available resources by the crop in terms of plant height. In this study, plant height was observed with a slower growth pattern up to 30 DAS and reached complete canopy cover by 90 DAS. Plant height continued to increase until harvest across two compact varieties. Among the compact varieties, CO 17 recorded taller plant heights at harvest and were found to be taller than VPT 2 during the summer and winter seasons, respectively. This may be due to the genetic makeup indicated (28). Plants grown during the winter season were consistently taller compared to those grown during the summer season and this might be due to favourable weather parameters has been resulted in the previous study (29, 30). Plant height at 60, 90 DAS and at harvest was higher with irrigation scheduled at 1.0 ETc with subsurface drip irrigation combinations. It was due to better availability of moisture content at all stages of crop growth. These results conform with previous research (31).

Plant height was increased continuously up to harvest. Subsurface drip irrigation level of 1.0 ETc recorded a higher plant height and was followed by 0.8 ETc at harvest. This might be due to the availability of higher moisture content near the root zone throughout the crop growth period with sub-surface drip irrigation, as indicated in the previous study (32) for both 1.0 ETc and 0.8 ETc.

Plant height of cotton was significantly increased due to the availability of optimal soil moisture and nutrients continuously at the root zone depth, preferring higher nutrient uptake and improved crop growth, which leads to taller plants as indicated (33). Moderately reduced subsurface drip irrigation regime with higher nitrogen levels recorded comparable plant height, this may be due to the continuous availability of moisture with higher nutrient uptake as suggested in the study (34).

Deficit irrigation at 1.0 ETc, combined with the compact cotton variety CO 17, promotes greater plant height by enhancing physiological efficiency. The use of nano nitrogen and conventional urea further supports this growth through balanced resource management. Under 1.0 ETc, the crop receives optimal water without over-saturation, maintaining root activity and stomatal conductance, which are critical for growth. CO 17, though genetically compact, responds positively to well-managed water and nitrogen regimes by enhancing internodal elongation and biomass partitioning to vegetative structures. The use of Nano urea allows for quick nitrogen absorption and translocation, stimulating early cell division and elongation, while conventional urea maintains a longer-duration nitrogen supply, ensuring continuous vegetative growth. This dual nitrogen approach enhances chlorophyll synthesis, photosynthesis and hormonal balance, all of which are vital for sustained height increase in cotton plants. Nano urea improves nitrogen use efficiency by over 30 %, directly influencing vegetative parameters like plant height under precise irrigation regimes (35).

The availability of irrigation water and nitrogen as per the requirement of the plants under sub-surface drip irrigation may be responsible for better plant height. The application of nano nitrogen also plays a major role in plant height. This might be due to the timely availability of nitrogen in adequate amounts for cell division and elongation as nitrogen is one of the major components for the growth of plants. The results also confirm the finding with previous study (36). This might be due to an increase in nutrient levels which enhance nutrient absorption, greater photosynthesis and proper distribution of the generated assimilates. Similar results were reported previously (37).

Monopodial branches per plant

The number of monopodial branches per plant is not significantly affected by deficit irrigation, compact varieties and nitrogen management. Zero monopodia in compact varieties are an important parameter needed for mechanical harvesting under HDPS conditions (38). Breeders generally design compact cultures with zero monopodia. Compact varieties inherently vary in their monopodial branch production, which could be due to genetic differences in growth habits and resource allocation. However, neither deficit irrigation nor compact varieties and nitrogen management significantly influenced this trait, indicating that monopodial branch formation in compact varieties is less responsive to cultivation practices, but relies more on intrinsic genetic factors.

Yield attributes

Yield is a function of growth and yield attributes per plant. Crop yield is a manifestation of various yield components like the number of bolls per plant, number of bolls per m^2 and boll weight. These attributes were at higher magnitude under 1.0 ETc irrigation regime through sub-surface drip. In the 1.0 ETc irrigation regime, soil remains always at the field capacity which enhanced all the growth attributes of the crop and resulted in maximum absorbed PAR accompanied by a higher rate of photosynthesis reflected in efficient translocation of photosynthates towards reproductive parts helped in an increase in yield attributing characters.

In contrast, the 0.6 ETc deficit irrigation regime resulted in significantly lower yield attributes because under stress conditions the relative water content in the leaves was decreased drastically and the stomata remained partially closed which inhibited the entry of carbon dioxide in the leaf tissue ultimately the rate of photosynthesis was reduced and thereby the reproductive organs were not supplied a significant amount of photosynthates for their growth and development. The results confirm those reported previously (39, 40).

The higher yield attributing parameters, like seed cotton yield per plant, can be related total number of bolls and boll weight. However, these were numerically higher in the sub-surface drip irrigation due to effective maintenance of soil moisture percent in the root zone. Higher yield parameters in sub-surface drip irrigation with 1.0 ETc, might be due to moisture supplied directly near root zone in the sub -surface drip irrigation which further helped in increased moisture absorption, photosynthesis and translocation of photosynthates to the developing bolls, besides producing and retaining a greater number of bolls per plant at later stages of the crop cycle.

Bolls per plant and bolls per m^2

Compact varieties showed distinct growth and yield patterns, reflecting their genetic potential. CO 17 consistently recorded a higher number of bolls per plant and bolls per m^2 during the summer and winter seasons, respectively, due to its superior reproductive capacity and retention, while VPT 2 registered lower boll counts, indicating its relatively lower efficiency in boll production and retention. This may be due to varietal differences in better assimilation and translocation of photosynthates to the reproductive sink, as suggested in the previous study (41).

The number of bolls per plant and per unit area is considered the first important contributor to seed cotton yield, followed by boll weight (42). Sub-surface drip irrigation level of 1.0 ETc registered a higher number of bolls per plant and per unit area. This was followed by 0.8 ETc. This was due to sufficient availability of moisture throughout the growing period with reduced ETc through sub-surface drip irrigation as suggested previously (43), reported a substantial increase in the number of bolls per plant with an increase in the rate of irrigation, where the highest number of bolls was observed in fully irrigated cotton compared to deficit irrigation levels, the result is confirmed in the following studies (44).

This factor might be due to the retention of optimum moisture in the root rhizosphere region, which meets the crop water demands needed for growth and production, as suggested in the studies (43). The integration of nano-nitrogen with conventional urea significantly increases the number of bolls per plant and per square meter in cotton, as it ensures enhanced nitrogen assimilation and sustained nutrient availability throughout the crop growth period. Nano urea provides rapid nitrogen uptake due to its nanoscale size, which supports early vegetative growth and higher retention of fruiting bodies, while conventional urea contributes to the long -term nitrogen pool, maintaining steady plant growth. This combination improves photosynthetic efficiency, chlorophyll content and assimilate partitioning, ultimately leading to more boll formation per plant and greater boll density per unit area. The synergistic nutrient effect supports better boll setting and reduces fruit drop, thereby improving productivity over conventional urea use alone (45). This is in confirmation of the early findings (46). The interaction of irrigation and nitrogen produced better boll production per m^2. This might be due to drip irrigation and nitrogen supplying the optimum level of nutrients with a sufficient moisture level, increasing nutrient uptake with better translocation of assimilates from source to sink, resulting in higher yield parameters (47). However, the higher yield of high-density planting was realized in this study by increasing the bolls per unit area.

Interaction of 1.0 ETc deficit irrigation in combination with the compact cotton variety CO 17 and integrated nitrogen management using nano nitrogen and conventional urea significantly enhances the number of bolls per plant and bolls m^{-2}. This effect is attributed to the efficient water and nutrient synchronization, where optimal moisture availability under 1.0 ETc supports root activity and nutrient uptake without excess vegetative growth. The compact architecture of CO 17 promotes better light interception and canopy aeration, facilitating uniform boll setting. Meanwhile, Nano urea ensures rapid nitrogen absorption, supporting early square formation and boll retention, while conventional urea provides sustained nitrogen supply during later stages. This integrated approach results in improved photosynthetic efficiency, sink strength and reproductive success, ultimately leading to higher boll density per plant and area under water-limited yet optimal conditions (48).

Single boll weight

The single boll weight in this study was not influenced by the cotton variety. The single boll weight in this study was found to be higher for fully satisfying crop evapotranspiration (1.0 ETc) and was comparable with 0.8 ETc. This might be due to increased moisture content in the root zone, resulting in high photosynthesis and efficient translocation of photosynthates which is reflected in higher boll weight as confirmed (49, 50). The combined application of nano nitrogen with conventional urea has been shown to enhance boll weight in cotton compared to the use of conventional urea alone. This synergistic effect arises from improved nitrogen use efficiency and sustained nutrient availability throughout critical growth stages. Nano urea, due to its ultra-small particle size, allows for faster absorption and translocation of nitrogen within the plant, ensuring immediate metabolic support during boll initiation and development. Meanwhile, conventional urea provides a baseline, slow-release nitrogen source, maintaining a prolonged nutrient supply. Together, this dual strategy enhances photosynthetic activity, protein synthesis and cell expansion, which are crucial for boll filling, ultimately resulting in heavier and more uniform bolls. Studies report that plots receiving a combination of nano and conventional urea produced significantly higher boll weights and overall yield compared to 100 % conventional urea alone (51). Similarly, a lack of nitrogen or excessive nitrogen reduces the boll weight because the synthesis and distribution of photosynthates were the results of various physiological processes which is constrained by nitrogen has been reported (52).

Seed cotton yield

Seed cotton yield is a complex character that involves the interaction of several intrinsic and external factors. It largely depends on the production and mobilization of carbohydrates, uptake of water and nutrients from the soil in addition to several environmental factors to which the plant is exposed during the growth period.

Compact cotton varieties like CO 17 exhibit short stature, early maturity and synchronous boll setting, enabling efficient light interception and nutrient utilization. These traits contribute to higher boll density. The compact architecture supports high-density planting, improving seed cotton yield (53). Seed cotton yield reflects the yield contributing parameters like boll number and boll weight. Seed cotton yield showed marked variation across the deficit irrigation, compact varieties and nitrogen management. CO 17 produced higher seed cotton yield compared to VPT 2 which could be attributed due to the better vegetative growth and profuse boll bearing. Maximum and higher seed cotton yields were recorded in the 1.0 ETc (2347 kg ha^{-1} in summer and 2255 kg ha^{-1} in winter). Under the 1.0 ETc irrigation regime, the soil moisture in the root zone remains always at field capacity throughout the crop growth period, which increases the vegetative growth and more interception of light and improves the light use efficiency resulting in increased photosynthetic rate and efficient translocation of photosynthates towards reproductive parts and finally leads to enhance the seed the cotton yield.

Seed cotton yield is the reflection of yield-attributing parameters like the number of bolls per plant and boll weight; this study realized the same. A sub-surface drip irrigation level of 1.0 ETc had significantly recorded higher seed cotton yield, which could be due to the better growth as a result of optimum soil moisture with lower ETc throughout the life cycle associated with subsurface drip irrigation without any stress period which increased the assimilates from source to sink for both 1.0 ETc as reported (54). Significantly lower seed cotton yield was observed under 0.6 ETc. This may be due to reduced available soil moisture, which eventually reduces vegetative growth, dry matter accumulation and seed cotton yield as suggested (55).

The increase in growth and yield attributes because of optimum moisture and nutrition to the crop through sub-surface drip irrigation was due to increased photosynthates and translocation of more assimilates from source to sink. Consequent to favorable effects on growth and yield attributes due to water and fertilizer application as per the need of the crop through the drip, significantly higher seed cotton yield was recorded under deficit irrigated conditions (56).

This might be due to better growth because of optimum moisture throughout the life cycle without any stress period, which increased the movement of assimilates from source to sink, with the previous study (6). The integration of nano-nitrogen contributed to a higher yield. This might be due to attributing parameters at better availability of soil moisture with optimum fertilizer, which was reflected in seed cotton yield. These findings are in close conformity with the study (57).

The development of compact cotton varieties has shown promising potential in enhancing crop resilience to abiotic stresses, particularly water scarcity. Selected compact varieties exhibit superior adaptability under limited irrigation regimes by maintaining physiological and reproductive functions, which in turn contribute to yield stability. This trait is particularly advantageous in regions prone to erratic rainfall or constrained water resources, where sustaining yield with reduced irrigation input is imperative for ensuring agricultural sustainability (58).

In parallel, the introduction of nano-urea as a novel fertilizer input offers a significant advancement in nitrogen management. Nitrogen is a key macronutrient essential for cotton vegetative growth, boll formation and fiber development. However, conventional urea application is frequently associated with inefficiencies due to losses via leaching, volatilization and denitrification. Nano-urea, due to its nanoscale dimensions and enhanced surface reactivity, improves nitrogen use efficiency by facilitating more efficient uptake and assimilation by plant roots (59). The higher surface area-to-volume ratio of nano-urea particles enhances interaction with root membranes, promoting rapid absorption and reducing losses.

Integrating nano-urea with optimized irrigation scheduling presents a synergistic opportunity to improve both water and nutrient use efficiencies. Coupling of nano-fertilizers with precision irrigation strategies such as deficit irrigation can lead to enhanced root-zone nutrient availability and improved crop water productivity. Such integration ensures that the timing and quantity of nutrient delivery coincide with critical growth stages, thereby maximizing seed cotton yield (60).

Moreover, the strategic combination of nano-urea with conventional urea has been shown to sustain crop yield while reducing total nitrogen input. Reported that replacing 25 % of conventional urea with nano-urea maintains yield levels comparable to 100 % conventional urea application. This substitution strategy not only reduces the environmental footprint associated with nitrogen fertilization but also has economic implications, lowering fertilizer costs without compromising productivity (61).

Collectively, these findings underscore the potential of adopting a holistic crop management approach that combines genotype selection (compact cotton varieties), nano-urea and deficit irrigation. Such integration can serve as a key strategy in enhancing the seed cotton yield.

Pairwise scatterplot matrix with correlation coefficients

The pairwise scatterplot matrix (Fig. 1) comprehensively visualizes the relationships between key agronomic traits, including plant height, number of bolls, monopodial branches, boll weight and yield. The diagonal panels display histograms with density plots, highlighting the distribution of each variable, while the upper triangular panels present Pearson correlation coefficients, indicating the strength of associations. The lower triangular panels contain scatterplots with fitted regression lines, illustrating the nature of

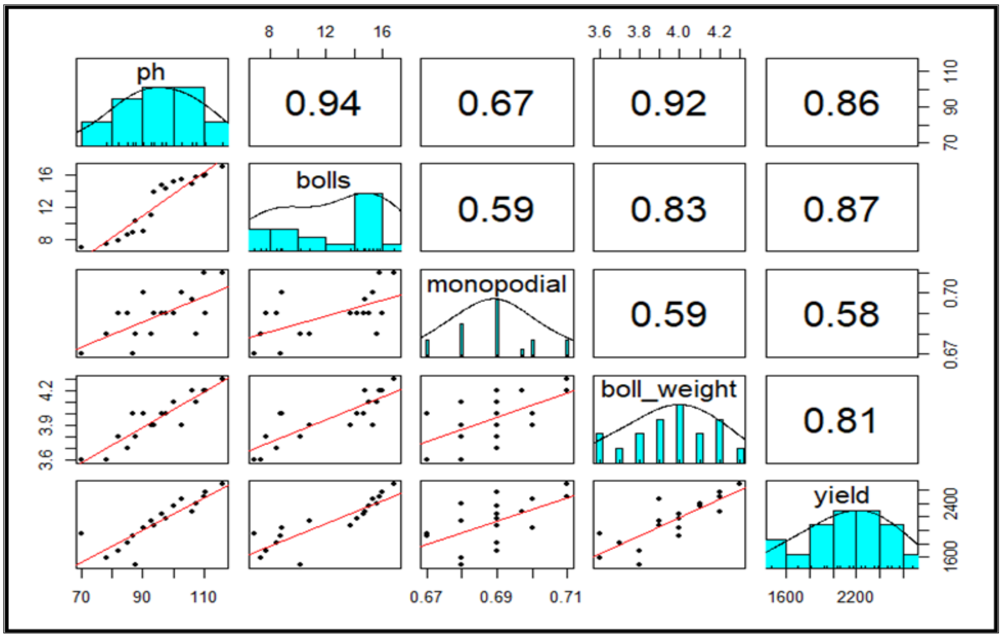

Fig. 1. Pairwise scatterplot matrix illustrating the relationships between plant height, number of bolls, monopodial branches, boll weight and yield.

relationships between the variables.

The analysis reveals strong positive correlations between plant height and yield (r = 0.86), boll weight (r = 0.92) and number of bolls (r = 0.94), suggesting that taller plants are associated with greater productivity. Similarly, boll weight and the number of bolls demonstrate strong correlations with yield (r = 0.81 and r = 0.87, respectively), reinforcing their role as primary contributors to overall productivity.

Conversely, monopodial branches exhibit a weaker correlation with yield (r = 0.58), indicating a lesser influence on yield determination. The scatterplots further confirm these relationships, with linear regression lines depicting positive associations between highly correlated variables.

Interpretation of Pearson correlation analysis of variables along with correlation matrix and heatmap

The correlation heatmap (Fig. 2) provides a structured visualization of the Pearson correlation coefficients among the studied agronomic traits. The intensity of the blue colour represents the strength of the association, with darker shades signifying stronger positive correlations. The results indicate a highly significant correlation between plant height and boll weight (r = 0.95), underscoring the role of plant stature in influencing boll development. Moreover, boll weight (r = 0.89) and the number of bolls (r = 0.85) maintain high correlations with yield, further emphasizing their importance in yield optimization. Conversely, monopodial branches exhibit the weakest correlation with yield (r = 0.55), suggesting a limited direct impact on productivity.

These findings collectively highlight the importance of selecting for plant height, boll weight and the number of bolls as primary determinants of yield, providing valuable insights for breeding programs and agronomic management strategies aimed at improving crop productivity.

Conclusion

From this study, it was concluded that sub-surface deficit drip irrigation levels of 1.0 ETc recorded comparable growth parameters, yield parameters and seed cotton compared to other reduced irrigation levels. In compact cotton varieties, CO 17 showed better growth and yield performance in both seasons compared to VPT 2. Among the nitrogen management, 50 % RDN through granular urea + split Nano urea treatment recorded the highest growth, yield parameters and yield compared to conventional nitrogen application through granular urea. To conclude that, in high-density cotton cultivation, the combination of CO17 compact variety under 1.0 ETc irrigation regime along with the application of 50 % RDN via granular urea and 50 % via staged Nano urea applications (25, 45 and 65 DAS) may be recommended through subsurface drip irrigation for higher productivity and profitability.

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Authors' contributions

MS conducted the experiment, recorded data and performed data analysis. SS supervised the experiment, formulated the experimental design, assisted and contributed to manuscript corrections and data analysis. PP, SA, RV and MBN offered guidance on experimenting with and correcting the manuscript. All authors reviewed and approved the final version of the manuscript.

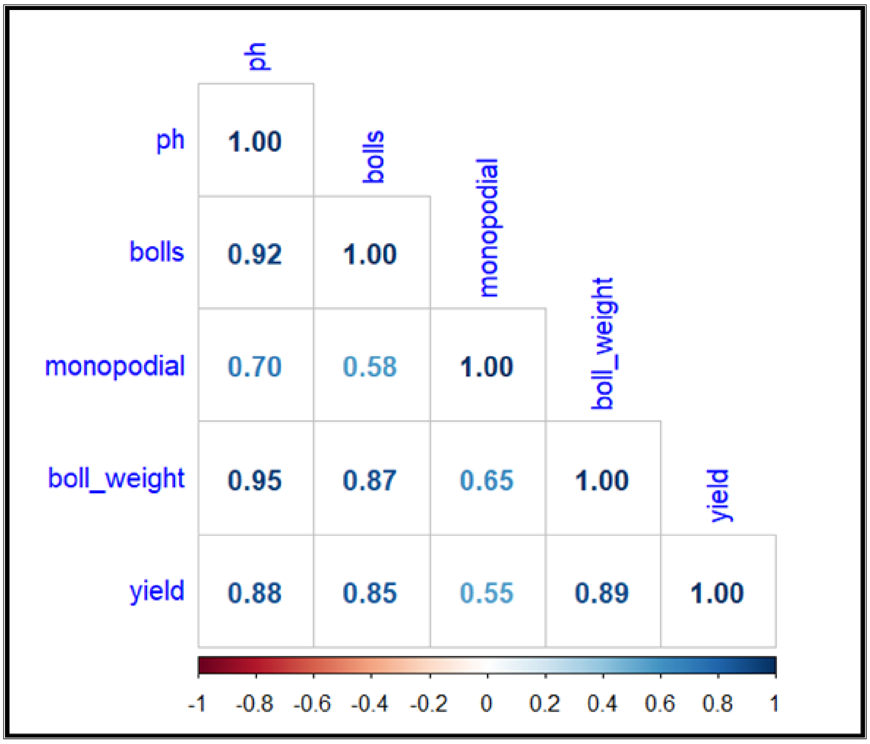

Fig. 2. Correlation heatmap showing the strength of relationships between plant height, number of bolls, monopodial branches, boll weight and yield.

Compliance with ethical standards

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

Ethical issues: None

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