CURRENT FARM SCIENCE
Volume 1 Issue 1 (July-Dec 2026) | e-ISSN: Applied | Page No: 1-24

Assessment of Fibre Quality Parameters and Water Productivity Indicators in High-Density Planted Cotton under Variable Irrigation and Nitrogen Levels.

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Article ID: CFS 001

Abstract

A field experiment was conducted during summer and winter seasons of 2024-25 at the Wetland Farm, Tamil Nadu Agricultural University, Coimbatore, to assess fibre quality parameters and water productivity indicators in high-density planted cotton under variable irrigation and nitrogen levels. The experiment was conducted in a split-split plot design with three replications, comprising three irrigation levels, viz., 1.0, 0.8 and 0.6 ETc through subsurface drip irrigation, two compact cotton varieties, CO 17 and VPT 2, and three nitrogen management practices, viz., no nitrogen (N1), 100% recommended dose of nitrogen (RDN) through granular urea (N2) and N3 (50% RDN through granular urea + 20% RDN through nano urea - 45DAS, 20% of Nano urea -45 DAS and 10% Nanourea at 65DAS. Fibre quality parameters and irrigation, total and economic water productivity were assessed. Irrigation levels significantly influenced elongation percentage, lint index and micronaire, whereas UHML, fibre strength, seed index and lint index were significantly influenced by compact varieties. The variety VPT 2 recorded higher UHML and fibre strength, while CO 17 recorded higher seed index and lint index. Nitrogen management significantly influenced lint index, with 50% RDN through granular urea + 50% RDN through nano urea recording higher values. Irrigation water productivity was higher under 0.6 ETc, while total and economic water productivity were generally higher under 1.0 ETc. CO 17 recorded higher water productivity than VPT 2, and N3 resulted in higher irrigation, total and economic water productivity. The results indicated that irrigation regime,

compact variety and nitrogen management differentially influenced fibre quality and water productivity indicators of high-density planted cotton.

Keywords: Cotton, Nitrogen level, Nano urea, Deficit Irrigation, Fibre Quality and Water Productivity

INTRODUCTION

Cotton (*Gossypium hirsutum* L.), often referred to as "King of fibres", is one of the most significant commercial fibre crops in the world. In India, cotton productivity has experienced a concerning decline in recent years, reaching its lowest levels in over a decade (Manibharathi *et al*., 2025). Despite being one of the largest global producers, the country faces stagnating yields mainly due to inappropriate water management practices, unsuitable varietal adaptation to local agro-climatic zones, imbalanced nitrogen management leading to excessive vegetative growth and pest infestation, along with climate vulnerability. In 2023-24, production declined to 294 lakh bales, marking an 8% reduction from the previous year (The Economic Times, 2023).

In recent years, High-Density Planting System (HDPS) has emerged as a promising technology for enhancing cotton yield and efficient water management is important for sustainable HDPS cotton production under irrigated conditions. Anticipated rise poses significant sustainability concerns, particularly in India. Addressing this challenge will require adoption of water-saving technologies and improved irrigation strategies to ensure sustainable cotton production by 2050 (Koudahe *et al*., 2021). Recent strategies, such as deficit subsurface drip irrigation, can reduce water use by 20-60% while maintaining yield, thus enhancing water use efficiency and supporting long-term sustainability (Xing *et al*., 2024).

Deficit irrigation in cotton cultivation is an effective water-saving strategy that involves applying less water than the full crop requirement, aiming to optimize yield in relation to water input (Manibharathi *et al*., 2024). Deficit irrigation through subsurface drip irrigation (SSDI) has emerged as a promising approach to improve water productivity (WP) as SSDI reduces evaporative losses and facilitates precise and efficient irrigation water management. SSDI irrigation improved the seed cotton yield by up to 31% over conventional methods, along with water savings of 44-57% (Khamidov *et al.,* 2024).

For the successful implementation of High Density Planting System (HDPS) under deficit subsurface drip irrigation, the use of suitable compact varieties along with efficient nitrogen management, plays a crucial role in maximizing yield and suitable new cotton varieties for HDPS are being developed in India (Kumar *et al*., 2024). Tamil Nadu Agricultural University

recently released compact cotton varieties CO 17 and VPT 2 designed to boost productivity under HDPS conditions due to their ability to thrive in closely spaced plantings while maintaining higher yield and quality.

Nitrogen management is crucial for optimizing cotton growth, yield and fibre quality. Proper nitrogen management ensures that plants receive adequate nutrition at critical stages, leading to improved productivity and reduced environmental concerns like nutrient runoff and emissions (Gupta *et al*., 2022). Recently, Nano urea offers enhanced absorption, targeted delivery and improved nitrogen use efficiency (Gousia *et al*., 2023). Combining application of conventional urea through fertigation and nano urea through foliar application can optimize nitrogen availability throughout growth stages, leading to better yield and reduced environmental impact in cotton (Bhone *et al*., 2024).

Cultivating HDPS cotton under appropriate deficit subsurface drip irrigation regime, with suitable compact cotton variety and adopting proper nitrogen management strategy offers a promising solution for cotton production in India. Specific objectives of the study were i) To assess effect of variable irrigation and nitrogen levels on fibre quality parameters of high-density planted cotton and ii) To evaluate influence of variable irrigation and nitrogen levels on WP indicators of high-density planted cotton.

MATERIALS AND METHODS

Field experiments were conducted during summer and winter seasons of 2024-25 at Field No. N3, Wetland Farm, Department of Agronomy, Tamil Nadu Agricultural University (TNAU), Coimbatore, located at 11° 07′ N and 77° 32′ E, with an elevation of 426.7 m MSL. Summer season (March-May) is characterized by high temperatures and dry weather conditions, whereas winter season, from November to February, experiences relatively cooler temperatures and occasional rainfall. The experimental site falls within the Western Agro-Climatic Zone of Tamil Nadu.

Treatment Details*:* The experiment was laid out in a split-split plot design with three replications, involving the following experimental factors:

Main Plot: Deficit Subsurface Drip irrigation

I_1 - 1.0 ETc

I_2 - 0.8 ETc

I_3 - 0.6 ETc

Sub Plot: Compact Varieties

V_1 - CO 17

V_2 - VPT 2

Sub-Sub Plot: Nitrogen Management

N_1 - Control

N_2 - 100 % RDN through granular urea

N_3 - 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

Methodology, data collection and analysis: Sample preparation: Seed cotton picked from each treatment after harvest was hand cleaned from contaminants, dried and ginned. Cleaned lint samples weighing 100 g each were packaged, labelled and submitted for fibre quality evaluation. Cotton samples were tested for fibre quality parameters at CIRCOT, CICR laboratory, Coimbatore for the following parameters:

a. Ginning percentage **(**Santhanam, 1976) .

$$\text{Ginning percentage (\%)} = \frac{\text{Weight of lint (g)}}{\text{Weight of seed cotton (g)}} \text{ X } 100$$

b. UHML: upper half mean length (UHML) represents average length of upper half of the fibers in a cotton sample and was measured and expressed in mm (Sundaram and Iyengar, 1968).

c. Length uniformity:

$$\text{Length of uniformity} = \frac{\text{Mean fiber length}}{\text{UHML}} \text{ X } 100$$

d. Fibre strength measured in measured in g tex^{-1}.

e. Elongation Percentage: It quantifies the proportional increase in length of a fiber when subjected to a defined amount of tensile force or stress. The elongation percentage was determined using a high-volume instrument and expressed in percentage.

f. Seed index: Seed index was determined to assess seed development by weighing 100 seeds collected from each treatment. The value was recorded in grams following the method described by Santhanam (1976).

g. Lint index:

$$\text{Lint index} = \frac{\text{Seed index x Ginning percentage (\%)}}{\text{100 - Ginning percentage (\%)}}$$

h. Micronaire value: Micronaire refers to air permeability of a compressed cotton sample. It indicates both fiber thickness (fineness) and maturity and is expressed in µg $inch^{-1}$ (Sundaram and Iyengar, 1968).

i. WP Indicators: The treatments were assessed using three WP indicators: irrigation WP (IWP), total water productivity (TWP), and economic water productivity (EWP). These parameters were calculated using the respective formulae described by Pereira *et al*. (2012), Sahoo et al. (2018), Jovanovic et al. (2020) and Palanisamy and Sivasamy (2009).

$$\text{Irrigation water productivity (Kg ha}^{-1}\text{ mm)} = \frac{\text{Seed cotton yield (Kg ha}^{-1}\text{)}}{\text{Irrigation water applied (mm)}}$$

$$\text{Economic water productivity (Rs. ha}^{-1}\text{ mm)} = \frac{\text{Gross income (Rs ha}^{-1}\text{)}}{\text{Total water use (mm)}}$$

Where, $\text{Total water use} = \text{Irrigation water} + \text{Effective rainfall}$

RESULTS AND DISCUSSION

Fibre Quality Parameters

Irrigation levels significantly influenced fibre quality parameters, including elongation percentage, lint index and micronaire, during both seasons. Among the compact varieties, significant differences were observed in upper half mean length (UHML), fibre strength, seed index, and lint index across both seasons (Table 1.). Nitrogen management practices significantly affected lint index in both seasons. However, ginning percentage and length uniformity were not significantly influenced by any of the treatments. Furthermore, interaction effects among

irrigation levels, compact varieties, and nitrogen management were non-significant for all fibre quality parameters evaluated.

UHML showed significant differences with compact varieties alone. VPT 2 recorded the highest UHML (30.9 and 29.9 mm), followed by CO 17 (29.4 and 28.6 mm) during both seasons. Fibre strength was significantly influenced by irrigation level in the winter season only. 1.0 ETc recorded the highest fibre strength (28.8 g tex^{-1}). The lowest fibre strength was recorded under 0.6 ETc deficit irrigation (27.4 g tex^{-1}) during winter season. Regarding compact varieties, VPT 2 recorded the highest fibre strength (29.7 and 29.4 g tex^{-1}), followed by CO 17 (28.3 and 26.5 g tex^{-1}) during both seasons (Table 1.).

Elongation percentage was significantly influenced by irrigation levels, with level 1.0 ETc recording the highest elongation percentage (5.8 and 5.8 %). The lowest elongation percentage was recorded under 0.6 ETc deficit irrigation (5.6 and 5.4%) during both seasons. Seed index showed significant differences with compact varieties alone. CO 17 recorded the highest seed index (8.2 and 8.2 g), followed by VPT 2 (7.1 and 6.9 g) during both seasons.

Lint index exhibited significant variation in response to all three experimental factors. The highest lint index was observed under 1.0 ETc irrigation level (5.3 and 5.8 g), followed by 0.8 ETc (4.8 and 5.5 g) and deficit irrigation with 0.6 ETc deficit irrigation recorded the lowest lint index (4.2 and 4.6 g) during both seasons. Regarding varieties, CO 17 recorded a higher lint index (5.2 and 5.9 g), followed by VPT 2 (4.3 and 4.6 g). Among nitrogen treatments, 50% RDN through granular urea + 50% RDN through nano urea recorded the highest lint index (5.0 and 5.7 g), followed by 100% RDN through granular urea (4.7 and 5.1), and the lowest was observed under no nitrogen application (4.6 and 5.0) during both seasons.

Micronaire was significantly influenced by irrigation levels. Higher micronaire values were recorded under 1.0 ETc (4.2 and 3.8 μg $inch^{-1}$), followed by 0.8 ETc (4.1 and 3.7 μg $inch^{-1}$), while the lowest values were under 0.6 ETc deficit irrigation (3.9 and 3.6) during both seasons. Interactions were absent during both seasons (Table 2.).

Table 1. Quality parameters of high-density planted cotton under variable irrigation and nitrogen levels during summer (S I) and winter (S II) seasons

Treatments	Ginning percentage		UHML (mm)		Length uniformity (%)		Fibre strength (g tex^{-1})	
	S I	**S II**	**S I**	**S II**	**S I**	**S II**	**S I**	**S II**
Deficit subsurface drip irrigation								
I_1 - 1.0 ETc	36.1	37.6	30.5	29.7	85.1	84.1	29.4	28.8
I_2 - 0.8 ETc	35.7	37.2	30.2	29.3	84.6	83.9	29.0	28.1
I_3 - 0.6 ETc	34.8	36.2	29.7	28.8	84.1	83.7	28.6	27.4
SEd	**0.30**	**0.31**	**0.26**	**0.25**	**0.7**	**0.6**	**0.25**	**0.20**
CD (p=0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**0.57**
Compact varieties								
V_1 - CO 17	35.7	37.2	29.4	28.6	84.7	84.0	28.3	26.5
V_2 - VPT 2	35.3	36.8	30.9	29.9	84.5	83.8	29.7	29.4
Sed	**0.56**	**0.59**	**0.48**	**0.47**	**1.34**	**1.33**	**0.47**	**0.42**
CD (p=0.05)	**NS**	**NS**	**1.1**	**1.1**	**NS**	**NS**	**1.1**	**1.0**
Nitrogen Management								
N_1 - No nitrogen application	35.2	36.6	30.0	29.1	84.4	83.6	28.9	27.5
N_2 - 100 % RDN through granular urea	35.5	36.9	30.2	29.3	84.7	84.0	29.0	28.1
N_3 - 50 % RDN through granular urea + 50 % RDN through nano urea	35.8	37.4	30.3	29.4	84.7	84.0	29.1	28.8
Sed	**0.78**	**0.82**	**0.66**	**0.65**	**1.87**	**1.86**	**0.64**	**0.63**
CD (p=0.05)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
Deficit subsurface drip irrigation x Compact varieties								
SEd	0.98	1.03	0.83	0.82	1.79	1.78	0.81	0.73
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Compact varieties x Nitrogen management								
SEd	1.11	1.16	0.94	0.92	2.55	2.53	0.91	0.89
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Deficit subsurface drip irrigation x Nitrogen management								
SEd	1.36	1.42	1.15	1.12	2.74	2.72	1.11	1.09
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Deficit subsurface drip irrigation x Compact varieties x Nitrogen management								
SEd	1.92	2.01	1.63	1.59	4.60	4.56	1.57	1.54
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Table 2. Attributes of high-density planted cotton under variable irrigation and nitrogen levels during summer (S I) and winter (S II) seasons

Treatments	Elongation percentage		Seed index (g)		Lint index (g)		Micronaire (µg inch^{-1})	
	S I	S II	S I	S II	S I	S II	S I	S II
Deficit subsurface drip irrigation								
I_1 - 1.0 ETc	5.8	5.8	7.8	7.6	5.3	5.8	4.2	3.8
I_2 - 0.8 ETc	5.7	5.6	7.7	7.6	4.8	5.5	4.1	3.7
I_3 - 0.6 ETc	5.6	5.4	7.6	7.5	4.2	4.6	3.9	3.6
SEd	**0.04**	**0.04**	**0.07**	**0.07**	**0.04**	**0.05**	**0.03**	**0.03**
CD (p=0.05)	**0.13**	**0.13**	**NS**	**NS**	**0.12**	**0.14**	**0.09**	**0.08**
Compact varieties								
V_1 - CO 17	5.7	5.6	8.2	8.2	5.2	5.9	4.1	3.7
V_2 - VPT 2	5.6	5.5	7.1	6.9	4.3	4.6	4.0	3.7
SEd	**0.08**	**0.08**	**0.12**	**0.12**	**0.07**	**0.08**	**0.06**	**0.05**
CD (p=0.05)	**NS**	**NS**	**0.30**	**0.30**	**0.19**	**0.21**	**NS**	**NS**
Nitrogen Management								
N_1 - No nitrogen application	5.5	5.4	7.6	7.4	4.6	5.0	4.0	3.6
N_2 - 100 % RDN through granular urea	5.7	5.6	7.7	7.6	4.7	5.1	4.1	3.7
N_3 - 50 % RDN through granular urea + 50 % RDN through nano urea	5.7	5.7	7.8	7.7	5.0	5.7	4.1	3.8
SEd	**0.12**	**0.12**	**0.17**	**0.16**	**0.10**	**0.11**	**0.09**	**0.08**
CD (p=0.05)	**NS**	**NS**	**NS**	**NS**	**0.22**	**0.24**	**NS**	**NS**
Deficit subsurface drip irrigation x Compact varieties								
SEd	0.11	0.11	0.17	0.17	0.10	0.11	0.08	0.07
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Compact varieties x Nitrogen management								
SEd	0.17	0.16	0.23	0.23	0.14	0.16	0.12	0.11
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Deficit subsurface drip irrigation x Nitrogen management								
SEd	0.18	0.18	0.25	0.25	0.15	0.20	0.13	0.12
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS
Deficit subsurface drip irrigation x Compact varieties x Nitrogen management								
SEd	0.27	0.27	0.37	0.37	0.23	0.28	0.19	0.18
CD (p=0.05)	NS	NS	NS	NS	NS	NS	NS	NS

Irrigation water productivity

Irrigation water productivity (IWP) was significantly affected by deficit subsurface drip irrigation, compact varieties, and nitrogen management during both seasons. Among the irrigation levels, 0.6 ETc recorded the highest irrigation water productivity, with values of 6.33 and 9.91 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively (Table 3.). This was followed by 0.8 ETc, which registered values of 5.58 and 9.04 kg ha^{-1} mm^{-1}, respectively. In contrast, the lowest irrigation water productivity was recorded under 1.0 ETc, with corresponding values of 5.07 and 8.46 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively.

Table 3. Irrigation water productivity (kg ha^{-1} mm^{-1}) of high-density planted cotton

Irrigation water productivity (IWP) (kg ha^{-1} mm^{-1})		
Treatments	**S I (Summer)**	**S II (Winter)**
Deficit subsurface drip irrigation		
I_1 - 1.0 ETc	5.07	8.46
I_2 - 0.8 ETc	5.58	9.04
I_3 - 0.6 ETc	6.33	9.91
SEd	**0.06**	**0.10**
CD (p=0.05)	**0.17**	**0.27**
Compact varieties		
V_1 - CO 17	5.81	9.39
V_2 - VPT 2	5.51	8.89
SEd	**0.08**	**0.14**
CD (p=0.05)	**0.21**	**0.34**
Nitrogen Management		
N_1 - No nitrogen application	4.66	7.45
N_2 - 100 % RDN through granular urea	6.01	9.71
N_3 - 50 % RDN through granular urea + 50 % RDN through nano urea	6.32	10.25

SEd	**0.12**	**0.20**
CD (p=0.05)	**0.26**	**0.42**
Deficit subsurface drip irrigation x Compact varieties		
SEd	0.15	0.24
CD (p=0.05)	NS	NS
Compact varieties x Nitrogen management		
SEd	0.18	0.29
CD (p=0.05)	NS	NS
Deficit subsurface drip irrigation x Nitrogen management		
SEd	0.22	0.36
CD (p=0.05)	NS	0.55
Deficit subsurface drip irrigation x Compact varieties x Nitrogen management		
SEd	**0.31**	**0.50**
CD (p=0.05)	**NS**	**NS**

Among the compact cotton varieties, CO17 exhibited significantly higher irrigation water productivity, recording 5.81 and 9.39 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively, compared with VPT 2, which recorded 5.51 and 8.89 kg ha^{-1} mm^{-1}, respectively. Regarding nitrogen management, combined application of 50% recommended dose of nitrogen (RDN) through granular urea and 50% RDN through nano urea resulted in the highest irrigation water productivity of 6.32 and 10.25 kg ha^{-1} mm^{-1} during summer and winter, respectively. This was followed by the application of 100% RDN through granular urea, which recorded values of 6.01 and 9.71 kg ha^{-1} mm^{-1}, respectively. The control registered the lowest irrigation water productivity, with values of 4.66 and 7.45 kg ha^{-1} mm^{-1} during respective seasons. However, interaction effects among deficit subsurface drip irrigation, compact varieties, and nitrogen management were non-significant.

Total water productivity

Total water productivity (TWP) varied significantly with deficit subsurface drip irrigation, compact cotton varieties, and nitrogen management practices during both seasons. Among irrigation treatments, 1.0 ETc level recorded the highest TWP values of 3.72 and 5.24 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively (Table 4.). This was followed by 0.8 ETc, which recorded values of 3.55 kg ha^{-1} mm^{-1} in summer and was comparable with the same

0.8 ETc with 5.23 kg ha^{-1} mm^{-1} in winter season. The lowest TWP was observed under 0.6 ETc deficit irrigation, with 3.37 and 4.96 kg ha^{-1} mm^{-1} during the respective seasons.

Among compact cotton varieties, CO 17 recorded higher total water productivity (TWP) values of 3.64 and 5.28 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively, compared with VPT 2, which registered 3.45 and 5.01 kg ha^{-1} mm^{-1}. Regarding nitrogen management, combined application of 50% recommended dose of nitrogen (RDN) through granular urea and 50% RDN through nano urea resulted in the highest TWP of 3.96 and 5.76 kg ha^{-1} mm^{-1} during summer and winter, respectively. This was followed by application of 100% RDN through granular urea, which recorded TWP values of 3.62 and 5.26 kg ha^{-1} mm^{-1}, respectively. The no nitrogen application recorded the lowest TWP of 3.06 and 4.41 kg ha^{-1} mm^{-1}(Table 4.).

Table 4. Total water productivity (kg ha^{-1} mm^{-1})

Total water productivity (TWP) (kg ha^{-1} mm^{-1})		
Treatments	**S I (Summer)**	**S II (Winter)**
Deficit subsurface drip irrigation		
I_1 - 1.0 ETc	3.72	5.24
I_2 - 0.8 ETc	3.55	5.23
I_3 - 0.6 ETc	3.37	4.96
SEd	**0.03**	**0.05**
CD (p=0.05)	**0.10**	**0.15**
Compact varieties		
V_1 - CO 17	3.64	5.28
V_2 - VPT 2	3.45	5.01
SEd	**0.05**	**0.07**
CD (p=0.05)	**0.13**	**0.18**
Nitrogen Management		
N_1 - No nitrogen application	3.06	4.41
N_2 - 100 % RDN through granular urea	3.62	5.26
N_3 - 50 % RDN through granular urea + 50 % RDN through nano urea	3.96	5.76
SEd	**0.08**	**0.11**
CD (p=0.05)	**0.16**	**0.24**

Deficit subsurface drip irrigation x Compact varieties		
SEd	0.07	0.11
CD (p=0.05)	NS	NS
Compact varieties x Nitrogen management		
V_1 x N_1	3.02	4.34
V_1 x N_2	3.91	5.69
V_1 x N_3	4.00	5.82
V_2 x N_1	3.11	4.48
V_2 x N_2	3.34	4.83
V_2 x N_3	3.91	5.70
SEd	**0.10**	**0.15**
CD (p=0.05)	**0.23**	**0.33**
Deficit subsurface drip irrigation x Nitrogen management		
I_1 x N_1	3.14	4.38
I_1 x N_2	3.88	5.46
I_1 x N_3	4.15	5.86
I_2 x N_1	2.93	4.28
I_2 x N_2	3.87	5.73
I_2 x N_3	3.85	5.70
I_3 x N_1	3.13	4.58
I_3 x N_2	3.13	4.59
I_3 x N_3	3.87	5.72
SEd	**0.12**	**0.17**
CD (p=0.05)	**0.25**	**0.37**
Deficit subsurface drip irrigation x Compact varieties x Nitrogen management		
I_1 x V_1 x N_1	3.23	4.51
I_1 x V_1 x N_2	3.97	5.59
I_1 x V_1 x N_3	4.25	6.01
I_1 x V_2 x N_1	3.04	4.26
I_1 x V_2 x N_2	3.79	5.33
I_1 x V_2 x N_3	4.05	5.72
I_2 x V_1 x N_1	3.03	4.42
I_2 x V_1 x N_2	4.11	6.10
I_2 x V_1 x N_3	3.78	5.58
I_2 x V_2 x N_1	2.83	4.13
I_2 x V_2 x N_2	3.64	5.37

I_2 x V_2 x N_3	3.93	5.82
I_3 x V_1 x N_1	2.82	4.10
I_3 x V_1 x N_2	3.64	5.38
I_3 x V_1 x N_3	3.97	5.87
I_3 x V_2 x N_1	2.61	3.80
I_3 x V_2 x N_2	3.45	5.06
I_3 x V_2 x N_3	3.77	5.57
SEd	**0.17**	**0.25**
CD (p=0.05)	**0.3 7**	**0.53**

The interaction between compact cotton varieties and nitrogen management practices indicated that CO 17 combined with 50% of recommended dose of nitrogen (RDN) through granular urea and 50% through nano urea achieved the highest total water productivity (TWP), recording 4.00 and 5.82 kg ha^{-1} mm^{-1} during summer and winter seasons, respectively. This was comparable with VPT 2 under same nitrogen management (3.91 and 5.70 kg ha^{-1} mm^{-1}) and also CO 17 under 100% RDN through granular urea (3.91 and 5.69 kg ha^{-1} mm^{-1}) during both seasons. Whereas the lowest TWP was found with CO 17 variety and no nitrogen application, which recorded 3.02 and 4.34 kg ha^{-1} mm^{-1} during both seasons (Table 4)..

The interaction between irrigation levels and nitrogen management practices revealed that 1.0 ETc irrigation with 50% RDN through granular urea + 50% RDN through nano urea resulted in the highest TWP of 4.15 and 5.86 kg ha^{-1} mm^{-1} during summer and winter. This was followed by I_1N_2 in summer and was comparable with I_2N_2, I_3N_3 in winter. The lowest water use efficiency was found under 0.8 ETc under no nitrogen application, which recorded 2.93 and 4.28 kg ha^{-1} mm^{-1}, respectively (Table 4).

Among three-way interactions, combination of 1.0 ETc with CO 17 under 50% RDN through granular urea + 50% RDN through nano urea recorded the highest TWP of 4.25 kg ha^{-1} mm^{-1} in summer. This was comparable with $I_1V_1N_2$, $I_1V_2N_3$, $I_2V_1N_2$, $I_2V_2N_3$ and $I_3V_1N_3$ in summer. During winter, combination of 0.8 ETc with CO 17 under 100% RDN through granular urea recorded the highest TWP of 6.10 kg ha^{-1} mm^{-1}. This was comparable with $I_1V_1N_2$, $I_1V_1N_3$, $I_1V_2N_3$, $I_2V_1N_3$, $I_2V_2N_3$, $I_3V_1N_3$ and $I_3V_2N_3$. The lowest TWP was recorded under 0.6 ETc with VPT 2 under no nitrogen application (2.61 and 3.80 kg ha^{-1} mm^{-1}) during both seasons.

Economic water productivity

Economic water productivity (EWP) varied significantly with deficit subsurface drip irrigation levels, compact cotton varieties, and nitrogen management practices during both seasons. Furthermore, significant interaction effects were observed among the experimental factors. Among irrigation, 1.0 ETc recorded the highest economic water productivity of 297.9 and 419.9 Rs. ha^{-1} mm^{-1} during summer and winter seasons and was followed by 0.8 ETc (284.4 Rs. ha^{-1} mm^{-1}) during summer and comparable with the same 0.8 ETc (419.8 Rs. ha^{-1} mm^{-1}) during winter. The lowest economic water productivity of 270.3 and 398.4 Rs. ha^{-1} mm^{-1} was under 0.6 ETc deficit irrigation (Table 5.). Regarding compact varieties, CO 17 recorded the highest economic water productivity of 291.7 and 425.4 Rs. ha^{-1} mm^{-1}, whereas VPT 2 recorded 276.7 Rs. ha^{-1} mm^{-1} and 401.2 Rs. ha^{-1} mm^{-1} during both seasons, respectively.

With respect to nitrogen management, combined application of 50% of the recommended dose of nitrogen (RDN) through granular urea and 50% through nano urea recorded the highest economic water productivity (EWP), with values of ₹316.8 and ₹461.7 ha^{-1} mm^{-1} during summer and winter seasons, respectively (Table 5.). This was followed by 100% RDN through granular urea with 290.4 and 421.7 Rs. ha^{-1} mm^{-1}, while the control (no nitrogen application) recorded the lowest economic water productivity of 245.3 and 353.5 Rs. ha^{-1} mm^{-1} during both seasons.

Interaction between compact varieties and nitrogen management revealed that CO 17 with 50% RDN through granular urea + 50% RDN through nano urea recorded the highest economic water productivity of 320.1 and 465.4 Rs. ha^{-1} mm^{-1} (V_1N_3), which was comparable with V_2N_3, V_1N_2, whereas CO 17 under control (no nitrogen application) recorded the lowest, with 242.2 and 347.3 Rs. ha^{-1} mm^{-1} during both seasons.

Table 5. Economic water productivity (Rs. ha^{-1} mm^{-1})

Economic water productivity (EWP) (Rs. ha^{-1} mm^{-1})		
Treatments	**S I (Summer)**	**S II (Winter)**
Deficit subsurface drip irrigation		
I_1 - 1.0 ETc	297.9	419.9
I_2 - 0.8 ETc	284.4	419.8
I_3 - 0.6 ETc	270.3	398.4
SEd	**2.8**	**3.7**
CD (p=0.05)	**7.7**	**10.5**

Compact varieties		
V_1 - CO 17	291.7	425.4
V_2 - VPT 2	276.7	401.2
SEd	**4.1**	**4.9**
CD (p=0.05)	**10.1**	**12.1**
Nitrogen Management		
N_1 - No nitrogen application	245.3	353.5
N_2 - 100 % RDN through granular urea	290.4	421.7
N_3 - 50 % RDN through granular urea + 50 % RDN through nano urea	316.8	461.7
SEd	**6.5**	**8.1**
CD (p=0.05)	**13.4**	**16.7**
Deficit subsurface drip irrigation x Compact varieties		
SEd	5.8	7.16
CD (p=0.05)	NS	NS
Compact varieties x Nitrogen management		
V_1 x N_1	242.2	347.3
V_1 x N_2	312.7	455.4
V_1 x N_3	320.1	465.4
V_2 x N_1	248.5	358.6
V_2 x N_2	267.1	387.0
V_2 x N_3	313.5	456.0
SEd	**8.0**	**10.6**
CD (p=0.05)	**18.0**	**22.8**
Deficit subsurface drip irrigation x Nitrogen management		
I_1 x N_1	251.3	350.2
I_1 x N_2	310.2	437.5
I_1 x N_3	332.2	469.8
I_2 x N_1	234.4	342.5
I_2 x N_2	310.3	459.6
I_2 x N_3	308.5	456.7
I_3 x N_1	250.4	366.8
I_3 x N_2	250.7	367.9
I_3 x N_3	309.7	457.5
SEd	**9.0**	**12.1**

CD (p=0.05)	**20.0**	**25.8**
Deficit subsurface drip irrigation x Compact varieties x Nitrogen management		
I_1 x V_1 x N_1	258.7	360.4
I_1 x V_1 x N_2	317.3	446.3
I_1 x V_1 x N_3	340.2	480.5
I_1 x V_2 x N_1	243.9	340.9
I_1 x V_2 x N_2	303.0	427.7
I_1 x V_2 x N_3	324.3	457.1
I_2 x V_1 x N_1	242.3	354.4
I_2 x V_1 x N_2	329.1	488.8
I_2 x V_1 x N_3	302.7	446.3
I_2 x V_2 x N_1	226.5	330.5
I_2 x V_2 x N_2	291.4	429.4
I_2 x V_2 x N_3	314.3	466.2
I_3 x V_1 x N_1	225.6	328.1
I_3 x V_1 x N_2	291.6	430.1
I_3 x V_1 x N_3	317.5	470.4
I_3 x V_2 x N_1	209.2	304.5
I_3 x V_2 x N_2	275.8	404.8
I_3 x V_2 x N_3	302.0	445.7
SEd	**14.0**	**17.3**
CD (p=0.05)	**29.0**	**36.6**

The interaction between irrigation levels and nitrogen management practices revealed that combination of 1.0 ETc irrigation with 50% of recommended dose of nitrogen (RDN) through granular urea and 50% through nano urea (I_1N_3) achieved the highest economic water productivity, recording 332.2 and 469.8 ₹ ha^{-1} mm^{-1} during summer and winter seasons, respectively. This was followed by I_1N_2, I_2N_2, I_2N_3, I_3N_3 in summer and was comparable with I_2N_2, I_2N_3, I_3N_3 in winter. The lowest economic water productivity was recorded with 0.8 ETc under control (no nitrogen application), which showed 234.4 and 342.5 Rs. ha^{-1} mm^{-1} during both seasons.

In three-way interaction, combination of 1.0 ETc with CO 17 under 50% RDN through granular urea + 50% RDN through nano urea recorded maximum economic water productivity of 340.2 Rs. ha^{-1} mm^{-1} during summer ($I_1V_1N_3$). This was comparable to the I1V1N2, $I_1V_2N_3$,

$I_2V_1N_2$, $I_2V_2N_3$ and $I_3V_1N_3$. During winter season, combination of 0.8 ETc irrigation, CO 17, and 100% of the recommended dose of nitrogen (RDN) through granular urea ($I_2V_1N_2$) recorded a higher economic water productivity of ₹488.8 ha^{-1} mm^{-1} and was statistically comparable with $I_1V_1N_2$, $I_1V_1N_3$, $I_1V_2N_3$, $I_2V_1N_3$, $I_2V_2N_3$, and $I_3V_1N_3$. The combination of 0.6 ETc irrigation, VPT 2, and no nitrogen application recorded the lowest economic water productivity, with values of ₹209.2 and ₹304.5 ha^{-1} mm^{-1} during summer and winter seasons, respectively (Table 5.).

Effect of deficit subsurface drip irrigation, compact varieties and nitrogen management on quality parameters

The fibre quality and yield traits of cotton, including ginning percentage, UHML, length of uniformity, fibre strength, elongation percentage, seed index, lint index and micronaire, were evaluated under varying irrigation levels, compact varieties and nitrogen management practices under subsurface drip irrigation in HDPS.

With respect to subsurface drip irrigation, although numerical variations were observed in ginning percentage and UHML across irrigation levels, the differences were statistically non-significant, indicating that these parameters are mainly governed by genetic factors (Bai *et al*., 2024). However, elongation percentage, lint index and micronaire were significantly influenced by irrigation regimes. The higher elongation percentage and micronaire values recorded under 1.0 ETc may be attributed to adequate and continuous moisture availability, which enhances cell elongation, fibre development and proper boll maturation (Yilmaz *et al*., 2021). In contrast, deficit irrigation (0.6 ETc) likely imposed moisture stress during critical growth stages, thereby affecting fibre elongation and fineness (Lin *et al*., 2024). Adequate moisture supply facilitates efficient assimilate translocation towards developing bolls, whereas moisture stress alters physiological processes associated with fibre development (Liao *et al*., 2024).

Among the compact varieties, significant differences were observed in UHML and fibre strength in addition to seed index and lint index. Variety VPT 2 recorded higher UHML and fibre strength compared to CO 17, indicating superior fibre length and strength characteristics, which are largely governed by genetic makeup. While, CO 17 exhibited higher seed index and lint index, suggesting better boll filling and assimilate partitioning efficiency under HDPS conditions as indicated by Tari *et al.* (2023). The significant differences observed in these traits reflect the genetic variability between the varieties in fibre development and yield-related characteristics.

These findings are in accordance with the reports of Cave (2013), who emphasized the predominant role of genotype in determining fibre quality traits such as length and strength.

In terms of nitrogen management, a significant difference was observed only in lint index during both seasons, while other fibre quality parameters remained unaffected. The combined application of 50% RDN through granular urea along with 50% RDN through nano urea recorded a higher lint index, followed by 100% RDN through granular urea, whereas the control recorded the lowest values. This improvement could be attributed to increased nitrogen availability and uptake, which support boll development and enhance lint accumulation per seed (Pettigrew and Zeng, 2014). However, the non-significant influence of nitrogen on ginning percentage, UHML, length uniformity and fibre strength suggests that nitrogen primarily affects yield components rather than intrinsic fibre quality traits. Comparable findings were reported by Zhong *et al*. (2013).

The interaction effects among irrigation levels, compact cotton varieties, and nitrogen management practices were non-significant for all fibre quality parameters evaluated, suggesting that these factors influenced fibre traits independently, without significant combined effects. Overall, the results suggest that while irrigation, variety and nitrogen management significantly influence certain yield-related attributes such as lint index and seed index, most fibre quality parameters remain stable and are predominantly governed by genetic factors. Thus, optimized agronomic management under HDPS can improve productivity without adversely affecting fibre quality.

Effect of deficit subsurface drip irrigation, compact varieties and nitrogen management on water productivity

In the present study, irrigation levels, compact cotton varieties, and nitrogen management practices significantly affected irrigation water productivity (IWP), total water productivity (TWP), and economic water productivity (EWP). As in many cases, in this study also, IWP and TWP varies involving deficit irrigation conditions, as water productivity often increases as water input decreases. Deficit irrigation enhanced IWP, expressed as yield per unit of irrigation water applied, more markedly than TWP, which represents yield per unit of total water use, including irrigation, effective rainfall, and soil moisture contribution. This difference was primarily attributed to the greater reduction in irrigation water applied under deficit irrigation (Fig. 1). Deficit irrigation of 0.6 ETc with lower irrigation water (301.3, 183.8 mm) recorded higher IWP

(6.33, 9.91 kg ha^{-1} mm^{-1}), followed by 0.8 ETc. Lower IWP (5.07, 8.46 kg ha^{-1} mm^{-1}) was observed by I.0 ETc, which received higher irrigation water (462.2, 266.3 mm). The findings are in line with Yamini and Singh (2024). Total water productivity registered a reverse trend as effective rainfall for soil moisture recharge increased in deficit irrigation treatments compared to yield increment. Irrigation at 1.0 ETc registered higher TWP (3.72, 5.24 kg ha^{-1} mm^{-1}), with less effective rainfall (167.7, 163.9 mm) and higher yields. A comparable performance was recorded under 0.8 ETc, indicating that moderate deficit irrigation can enhance water savings without substantial yield reductions. In contrast, 0.6 ETc deficit irrigation resulted in the lowest TWP (3.37, 4.96 kg ha^{-1} mm^{-1}), due to higher effective rainfall contributions (263.9, 183.2 mm) and related lower yield increments, reflecting the adverse effects of excessive water deficit, as noted by Nalayini et al. (2006) and Yilmaz et al. (2021). Economic water productivity relating gross returns and yield also followed the TWP trend where 1.0 ETc > 08 ETc > 0.6 ETc, as indicated by Somasundaram (2004) while evaluating low-cost drip irrigation in cotton.

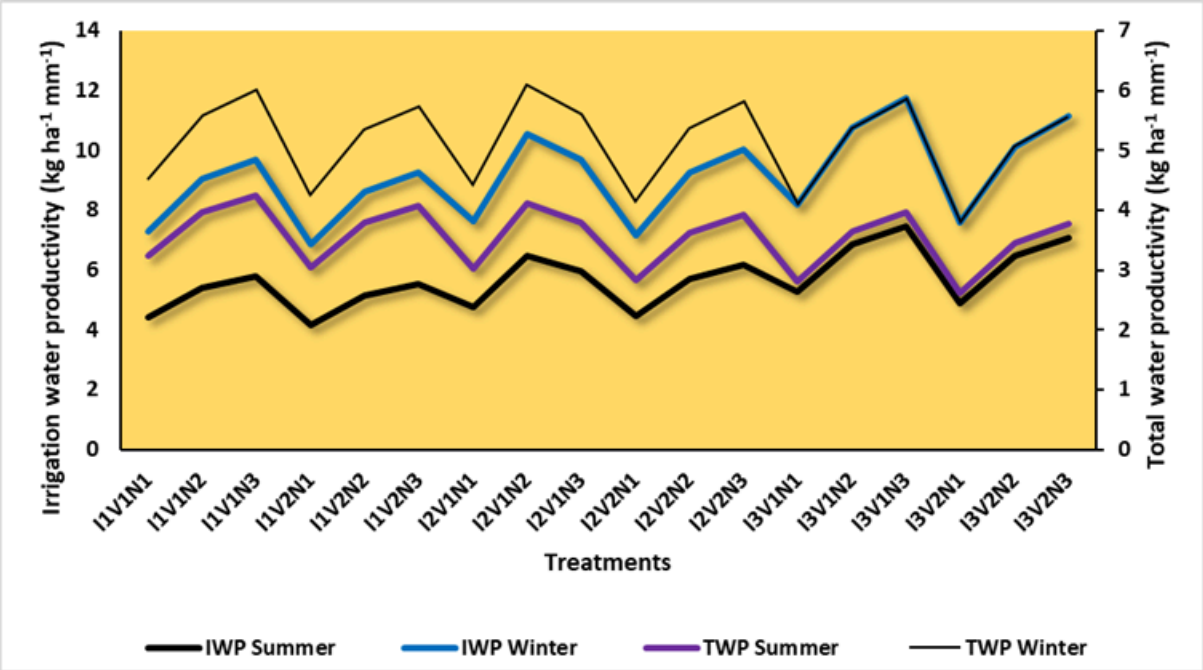


Fig. 1. Irrigation water productivity (kg ha^{-1} mm^{-1}) and total water productivity (kg ha^{-1} mm^{-1}) of high-density planted cotton under variable irrigation and nitrogen levels during summer (S I) and winter (S II) seasons

The compact cotton variety CO 17 exhibited superior IWP, TWP and EWP compared to VPT 2. This enhanced efficiency highlights its adaptability under water-limited conditions and

its potential to sustain yield with reduced irrigation. Specifically, higher IWP under CO 17 indicates its suitability for regions facing water scarcity, making it a promising choice for improving resource-use efficiency in HDPS. These findings are consistent with the results reported by Anbarasan et al. (2023).

Application of 50% RDN through granular urea combined with 50% RDN through nano urea achieved higher IWP, TWP and EWP compared to other N management strategies. This improvement may be attributed to the better synchronization of nitrogen availability with crop demand through split applications, coupled with the enhanced nitrogen use efficiency (NUE) associated with nano urea, thereby promoting greater biomass accumulation and yield development. The importance of efficient nutrient delivery methods in maximizing the benefits of applied water (Satale et al., 2024). Efficient nitrogen supply in conjunction with efficient irrigation enhances crop water productivity by synchronizing nutrient uptake with water availability (Sorensen et al., 2004).

Higher and comparable TWP and EWP are recorded in combination of 1.0 ETc with CO 17 under 50% RDN through granular urea + 50% RDN through nano urea and 0.8 ETc with CO 17 under 100% RDN through granular in different seasons, confirming that synchronizing water and nitrogen supply is essential for maximizing water productivity, consistent with the findings of Janat (2008).

CONCLUSION

The study demonstrated that irrigation regime, compact cotton variety and nitrogen management influenced specific fibre quality parameters and water productivity indicators of high-density planted cotton. Irrigation levels significantly affected elongation percentage, lint index and micronaire, while compact varieties significantly influenced UHML, fibre strength, seed index and lint index. VPT 2 recorded superior UHML and fibre strength, whereas CO 17 recorded higher seed index and lint index. Similarly, Nitrogen management significantly influenced lint index, with 50% RDN through granular urea + 50% RDN through nano urea recording higher values. Irrigation water productivity increased with deficit irrigation and was highest under 0.6 ETc, reflecting greater productivity each unit of irrigation water used. In contrast, total and economic water productivity were generally higher under 1.0 ETc, indicating the contribution of adequate irrigation to overall water productivity under the experimental conditions. CO 17 recorded higher irrigation, total and economic water productivity than VPT 2.

Overall, the findings demonstrate that water productivity indicators respond differently depending on the component of water use considered, while fibre quality responses vary among irrigation, variety and nitrogen management factors. The findings emphasize the significance of combining suitable irrigation practices, compact cotton varieties, and efficient nitrogen management to enhance resource-use efficiency while maintaining desirable fibre quality under high-density cotton cultivation.

Declarations and staements

Acknowledgements

Authors gratefully acknowledge Tamil Nadu Agricultural University, Coimbatore, and Cotton Research Station, Veppanthattai, for providing necessary research facilities to conduct the experiments successfully.

Authors' contributions

MS conducted the experiment, collected data and performed statistical analysis. SS supervised experiments, designed the study and contributed to data analysis and manuscript revision. SA, RV, MBN and GR provided scientific guidance throughout experimental work and contributed to manuscript revision. All authors reviewed and approved the final manuscript.

Conflict of interest: The authors declare that they have no conflicts of interest.

Ethical issues: None

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