



RESEARCH ARTICLE

Influence of smart irrigation techniques and soil amendments on growth dynamics and yield performance of cotton in western zone of Tamil Nadu

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Abstract

Cotton (*Gossypium hirsutum* L.) is an important commercial crop and its productivity is highly influenced by efficient water and nutrient management, especially under changing climatic conditions. A field experiment was conducted during the summer and winter seasons of 2025–26 at the experimental fields of Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, to evaluate the effect of smart irrigation techniques and soil amendments on the growth and yield performance of cotton. The experiment was laid out in a strip-plot design with 3 replications. The main-plot treatments consisted of different smart irrigation techniques, viz., drip irrigation, soil moisture sensor-based drip irrigation and evapotranspiration (ET)-based drip irrigation. The sub-plot treatments comprised combinations of liquid biofertilisers (nitrogen-fixing bacteria (NFB), phosphorus-solubilising bacteria (PSB) and phosphorus-mobilising bacteria (PMB), each at 5 L ha⁻¹), zeba at 12.5 kg ha⁻¹ and enriched farmyard manure (EFYM) at 7.5 t ha⁻¹. The results revealed that soil moisture sensor-based drip irrigation combined with liquid biofertilisers, zeba and EFM significantly improved growth parameters, dry matter production and seed cotton yield during both seasons. The integrated treatment also enhanced soil moisture availability, nutrient uptake efficiency and overall crop productivity. The highest plant height (124.26 and 127.88 cm), number of sympodial branches per plant (32.11 and 30.40), dry matter production (12574 and 11745 kg ha⁻¹), number of bolls per plant (14.0 and 13.5) and seed cotton yield (3728 and 3571 kg ha⁻¹) were recorded under soil moisture sensor-based drip irrigation combined with liquid biofertilisers, zeba and EFM during the summer and winter seasons, respectively. Therefore, the combined can be recommended for enhancing cotton productivity and resource-use efficiency.

Keywords: enriched farmyard manure; liquid biofertilisers; soil moisture sensor; superabsorbent polymer; water-use efficiency

Introduction

Cotton (*Gossypium hirsutum* L.) is one of the most important commercial fibre crops in India and serves as the backbone of the country's textile industry, which is among the largest organised sectors in the nation. Owing to its significant contribution to foreign exchange earnings, industrial development and employment generation, cotton is popularly referred to as “White Gold” (1). India is one of the leading cotton-producing countries in the world, cultivating cotton over an area of 115 lakh hectares, with a production of 297 lakh bales (each bale weighing 170 kg) and an average productivity of 440 kg ha⁻¹. In Tamil Nadu, cotton is cultivated over an area of 1.02 lakh hectares, with a production of 2.11 lakh bales and an average productivity of 350 kg ha⁻¹ (2). Besides its economic importance, cotton plays a vital role in sustaining the livelihoods of millions of farmers and workers involved in cultivation, processing and trade activities (3).

In spite of improved production technologies, cotton productivity in many regions remains below its potential due to irregular rainfall, moisture stress, poor nutrient-use efficiency and imbalanced crop management practices (4). Under changing climatic conditions and increasing water scarcity, efficient irrigation and nutrient management have become essential for sustaining crop productivity (5). Increasing planting density alone may not ensure higher yields unless it is supported by improved agronomic practices and suitable cultivars. Appropriate spacing, timely irrigation, balanced nutrient management and effective pest control are crucial for enhancing crop growth and productivity. Moreover, cultivars possessing early maturity, disease resistance and high yield potential can further improve performance under intensive cultivation systems (6). However, inefficient irrigation practices often result in substantial water losses, whereas the indiscriminate use of chemical fertilisers deteriorate soil health, reduces nutrient-use efficiency and adversely affects beneficial microbial activity (7).

Among the various irrigation methods, drip irrigation has emerged as an efficient water management technique for cotton cultivation because it supplies water and nutrients directly to the active root zone, thereby improving water-use efficiency and minimising evaporation, runoff and deep percolation losses (8). Compared with conventional irrigation methods, drip irrigation can save nearly 50–60 % of irrigation water (9). Furthermore, the integration of sensor-based irrigation systems facilitates real-time soil moisture monitoring and precise irrigation scheduling, thereby reducing moisture stress and improving crop performance (10).

Integrated nutrient management through the application of biofertilisers and organic amendments further enhances soil fertility and nutrient availability. Liquid biofertilisers containing nitrogen-fixing, phosphorus-solubilising and potassium-mobilising microorganisms improve nutrient-use efficiency, while enriched farmyard manure (EFYM) enhances soil structure, microbial activity and water-holding capacity (11, 12). Zeba, a biodegradable superabsorbent polymer, enhances soil moisture conservation by absorbing and gradually releasing water into the root zone, thereby reducing drought stress and improving cotton establishment. It significantly enhanced cotton seedling emergence by 17.9–22.6 % and reduced the mean emergence time by 36–46 % under water-stress conditions compared with the untreated control (13).

Therefore, smart irrigation techniques, particularly soil moisture sensor-based drip irrigation, combined with soil amendments such as liquid bio fertilisers, EFYM and zeba, would enhance soil moisture availability, nutrient-use efficiency and soil health, thereby improving the growth, yield attributes and seed cotton yield of *Bacillus thuringiensis* (Bt) cotton compared with conventional irrigation and amendment practices.

Materials and Methods

The experiment was conducted at the experimental fields of Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, during summer 2025 and winter 2025–26. The experimental site is geographically located at 11°00' N latitude and 76°92' E longitude, at an altitude of 426.7 m above mean sea level. The experiment was conducted during the summer and winter seasons of 2025–26. The experimental field soil was clay loam in texture, slightly alkaline in reaction, with a pH of 8.1 and 7.8 and an electrical conductivity (EC) of 0.41 and 0.17 dS m⁻¹ during the summer and winter seasons, respectively. The soil was low in available nitrogen (209 and 212 kg ha⁻¹), medium in available phosphorus (21 and 18 kg ha⁻¹), high in available potassium (434 and 410 kg ha⁻¹) and contained organic carbon of 0.70 and 0.65 %, respectively, during the summer and winter seasons. The weather conditions during the summer 2025 season were characterised by a mean daily rainfall of 1.66 mm, a maximum temperature of 31.19 °C, a minimum temperature of

22.60 °C, a relative humidity of 78.63 % and a wind speed of 2.50 m s⁻¹. During the winter 2025–26 season, the mean daily rainfall was 1.10 mm, the maximum temperature was 29.21 °C, the minimum temperature was 18.84 °C, the relative humidity was 79.24 % and the wind speed was 1.89 m s⁻¹. The total irrigation water applied (mm), as influenced by smart irrigation techniques during both the seasons, is presented in Table 1.

The site falls within the western agro-climatic zone of Tamil Nadu. A strip-plot design with three replications was adopted. The cotton variety RCH 929 BG II was selected for use in the study with a spacing of 90 × 15 cm and the seeds were purchased from Rasi seeds, Salem. Liquid biofertilisers comprising nitrogen-fixing bacteria (NFB), phosphate-solubilising bacteria (PSB) and potassium-mobilising bacteria (PMB), each applied at 5 L ha⁻¹, were procured from the TNAU biofertiliser production unit and used as a seed treatment prior to sowing. Zeba® is a biodegradable starch-based superabsorbent polymer. The product is composed of cross-linked cornstarch-based hydrogel granules capable of absorbing and gradually releasing water in the root zone. Zeba was applied as a basal soil amendment at 12.5 kg ha⁻¹ to improve soil moisture retention.

The treatment details are as follows

Main-plot treatments (smart irrigation techniques)

- I₁: Drip irrigation system
- I₂: Soil moisture sensor based irrigation- real-time irrigation scheduling through a drip irrigation system based on soil moisture sensor data
- I₃: Weather-based irrigation-irrigation scheduling through a drip irrigation system based on crop evapotranspiration (ET) rates and weather forecasts

Sub-plot treatments (soil amendments)

- A₁: Control
- A₂: Basal application of EFYM at 7.5 t ha⁻¹
- A₃: Application of liquid biofertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹)
- A₄: Basal application of Zeba at 12.5 kg ha⁻¹
- A₅: Basal application of EFYM at 7.5 t ha⁻¹ + application of liquid biofertilisers (NFB, PSB and PMB each at 5 L ha⁻¹)
- A₆: Basal application of EFYM at 7.5 t ha⁻¹ + basal application of zeba 12.5 kg ha⁻¹
- A₇: Application of liquid biofertilisers (NFB, PSB and PMB each at 5 L ha⁻¹) + basal application of zeba at 12.5 kg ha⁻¹
- A₈: Basal application of EFYM at 7.5 t ha⁻¹ + application of liquid biofertilisers (NFB, PSB and PMB each at 5 L ha⁻¹) + basal application of zeba at 12.5 kg ha⁻¹

Table 1. Total irrigation water applied (mm) as influenced by smart irrigation techniques during summer 2025 and winter 2025–26

Treatments	Total irrigation water applied (mm) for each treatment					
	Summer 2025			Winter 2025–26		
	I ₁	I ₂	I ₃	I ₁	I ₂	I ₃
A ₁	800	700	750	730	680	680
A ₂	750	650	700	680	580	630
A ₃	700	650	700	630	580	630
A ₄	650	550	600	580	480	530
A ₅	700	600	650	630	530	580
A ₆	650	550	600	580	480	530
A ₇	650	550	600	580	480	530
A ₈	650	500	550	580	430	480

The experimental field was ploughed using a tractor-drawn five-tine cultivator, followed by two additional ploughings with the cultivator. Subsequently, the soil clods were broken using a rotavator to obtain a fine tilth. The field was then uniformly levelled and beds were formed using a tractor-drawn broad-bed former. Healthy and viable seeds of hybrid cotton (RCH 929 BG II) were sown at a spacing of 90×15 cm. Gap filling and thinning were carried out to maintain the optimum plant population. As recommended, pendimethalin at $1.0 \text{ kg a.i. ha}^{-1}$ was applied as a pre-emergence herbicide followed by hand weeding. The experimental field was irrigated with borewell water. A life irrigation was applied three days after sowing (DAS). The treatments were imposed as per the schedule. Necessary plant protection measures were undertaken to control sucking pests; consequently, a single application of imidacloprid $17.8 \text{ \% SL}$ at 4 mL L^{-1} of water.

The biometric observations, such as growth attributes, viz. plant height and dry matter production and yield attributes, viz. number of monopodial branches per plant, number of sympodial branches per plant, number of bolls per plant, boll weight and seed cotton yield, were recorded periodically. The data were analysed using analysis of variance (ANOVA) for a strip-plot design and treatment means were compared using the least significant difference (LSD) test at $P \leq 0.05$ (14). The critical differences were worked out at 5 % probability for significant mean differences and interpreted. The methodologies adopted for data recording are described below.

Plant height (cm)

Plant height was measured from the base of the plant to the tip of the uppermost fully expanded leaf using a metre scale. Observations were recorded at 30, 60 and 90 DAS and at harvest, from five randomly selected and tagged plants in each plot. The average values were calculated and expressed in centimetres (cm).

Dry matter production (kg ha^{-1})

Plant samples for estimating dry matter production were collected at 30, 60 and 90 DAS and at harvest. Five plants from each treatment were randomly selected and carefully uprooted at ground level. The collected samples were first air-dried and then oven-dried at $80 \pm 5^\circ\text{C}$ until a constant weight was attained. The dry matter production was computed and expressed in kilograms per hectare (kg ha^{-1}).

Number of monopodial branches per plant

The number of monopodial branches arising from the axillary buds of five tagged plants was recorded at 120 DAS. The mean number of monopodial branches per plant was calculated and expressed accordingly.

Number of sympodial branches per plant

The number of sympodial (fruiting) branches emerging from the extra-axillary buds of five selected plants was counted at 120 DAS in each treatment. The mean number was calculated and expressed as the number of branches per plant.

Number of bolls per plant

The total number of mature bolls retained on each of the five tagged plants in each treatment plot was counted before harvest. The mean value was calculated and expressed as the number of bolls per plant.

Boll weight (g boll^{-1})

Fully opened and mature bolls harvested from five tagged plants

were collected and weighed using a precision balance. The mean boll weight was calculated and expressed in grams per boll (g boll^{-1}).

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

Seed cotton yield was estimated by harvesting the produce from the net plot area of each treatment separately. The harvested kapas was shade-dried, weighed and the yield was converted to kilograms per hectare (kg ha^{-1}).

Results

Impact of treatments on growth attributes

Plant height

Plant height was significantly influenced by different irrigation regimes and soil amendment treatments during both the summer and winter seasons. At 30 DAS, during the summer season, the drip irrigation system (I_1) recorded the highest plant height (20.17 cm), while the lowest plant height was observed under weather-based irrigation scheduling (I_3) (15.53 cm). However, at the subsequent growth stages (60 DAS, 90 DAS and harvest), soil moisture sensor-based irrigation (I_2) resulted in significantly greater plant heights of 53.82, 94.47 and 117.51 cm, respectively. In contrast, the lowest plant heights at these stages were recorded under drip irrigation alone (I_1) with corresponding values of 47.55, 85.95 and 110.23 cm. A similar pattern was observed during the winter season, where soil moisture sensor-based irrigation (I_2) consistently produced taller plants at the later growth stages compared to the other irrigation treatments (Table 2).

Among the soil amendment treatments, the application of liquid biofertilisers comprising NFB, PSB and PMB, each at 5 L ha^{-1} together with zeba at 12.5 kg ha^{-1} as a basal application and EFYM at 7.5 t ha^{-1} (A_8) recorded significantly greater plant height at all growth stages (23.79, 56.56, 99.26 and 122.13 cm at 30 DAS, 60 DAS, 90 DAS and harvest, respectively) which was comparable with the application of liquid biofertilisers (NFB, PSB and PMB each, at 5 L ha^{-1}) + zeba at 12.5 kg ha^{-1} as a basal application (A_7), which recorded plant heights of 22.56, 55.63, 97.80 and 120.14 cm, respectively. The lowest plant height was recorded under the untreated control (A_1) with values of 11.17, 41.29, 78.39 and 102.37 cm at the respective growth stages during the summer season. Similar observations were recorded during the winter season.

The interaction effect between irrigation and soil amendment treatments was non-significant at 30 DAS in both seasons; however, significant interaction effects were observed at 60 DAS, 90 DAS and harvest. Among the interaction combinations, soil moisture sensor-based irrigation through a drip system coupled with the application of liquid biofertilisers of NFB, PSB and PMB, each at 5 L ha^{-1} together with zeba at 12.5 kg ha^{-1} and EFYM at 7.5 t ha^{-1} (I_2A_8) registered the greatest plant height of 61.20, 101.05 and 124.26 cm at 60 DAS, 90 DAS and harvest, respectively. This treatment was statistically comparable with soil moisture sensor-based irrigation through a drip system combined with the application of liquid biofertilisers (NFB, PSB and PMB, each at 5 L ha^{-1}) + zeba 12.5 kg/ha as a basal application (I_2A_7), which recorded plant heights of 59.10, 100.55 and 124.05 cm, respectively. The minimum plant height was observed under the interaction combination I_1A_1 (drip irrigation with the control), which recorded plant heights of 39.79, 78.34 and 102.68 cm at corresponding stages during the summer season. Similar trends were also observed during the winter season (Tables 3 and 4).

Table 2. Effect of irrigation and soil amendments on plant height during summer 2025 and winter 2025–26

Treatments	Summer 2025				Winter 2025–26			
	30 DAS	60 DAS	90 DAS	At harvest	30 DAS	60 DAS	90 DAS	At harvest
I ₁	20.17	47.55	85.95	110.02	20.99	49.13	86.85	110.25
I ₂	17.03	53.82	94.47	117.51	17.84	55.23	95.62	119.32
I ₃	15.53	48.88	88.11	111.73	16.41	50.21	88.86	111.99
SEd	0.50	0.69	0.87	0.68	0.38	0.50	0.53	0.87
CD	1.41	1.91	2.43	1.89	1.07	1.39	1.49	2.43
A ₁	11.17	41.29	78.39	102.37	12.02	43.2	78.77	101.75
A ₂	12.91	46.4	83.78	108.67	13.46	47.47	84.63	108.31
A ₃	14.89	48.37	86.18	110.42	15.31	49.84	87.09	111.49
A ₄	16.23	47.37	84.78	109.51	1747.39	48.53	85.76	110.35
A ₅	19.15	51.94	91.92	115.22	19.79	52.99	92.33	116.2
A ₆	19.90	53.1	93.96	116.42	21.00	54.59	94.9	117.44
A ₇	22.56	55.63	97.80	120.14	23.55	57.03	99.17	121.87
A ₈	23.79	56.56	99.26	122.13	24.78	58.52	100.9	123.43
SEd	0.51	1.11	2.49	2.51	0.56	0.88	2.22	4.03
CD	1.10	2.39	5.36	5.39	1.20	1.90	4.77	8.64
Irrigation x Soil amendments								
SEd	1.29	1.86	2.98	3.52	1.27	1.65	2.84	4.67
CD	NS	4.01	6.30	7.32	NS	3.50	5.90	9.68
Soil amendments x Irrigation								
SEd	1.16	1.88	3.53	3.97	1.19	1.63	3.30	5.68
CD	NS	3.91	7.40	8.37	NS	3.40	6.90	11.91

DAS: days after sowing.

Table 3. Interaction effect of irrigation and soil amendments of plant height during summer 2025

Treatments	60 DAS				90 DAS				At harvest			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	39.79	42.09	42.00	41.29	78.34	78.46	78.37	78.39	102.68	102.98	102.72	102.79
A ₂	45.40	50.20	43.60	46.4	81.57	91.01	78.75	83.78	107.94	113.73	104.35	108.67
A ₃	46.60	53.40	45.10	48.37	82.53	95.88	80.15	86.18	108.36	116.9	106.00	110.42
A ₄	44.90	49.10	48.10	47.37	79.42	88.47	86.46	84.78	105.93	112.16	110.44	109.51
A ₅	47.10	56.83	51.90	51.94	83.66	100.10	92.02	91.92	107.79	122.88	115.01	115.22
A ₆	48.60	58.60	52.10	53.1	87.77	100.21	93.90	93.96	110.75	123.1	115.41	116.42
A ₇	53.80	59.10	54.00	55.63	96.09	100.55	96.76	97.80	117.48	124.05	118.90	120.14
A ₈	54.20	61.20	54.28	56.56	98.23	101.05	98.50	99.26	120.94	124.26	121.19	122.13
Mean	47.55	53.82	48.88		85.95	94.47	88.11		110.23	117.51	111.75	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI	I	A	IxA	AxI
SEd	0.69	1.11	1.86	1.88	0.87	2.49	2.98	3.53	1.08	3.11	3.02	3.97
C.D	1.91	2.39	4.01	3.91	2.43	5.36	6.30	7.40	3.01	6.68	6.47	8.37

DAS: days after sowing.

Table 4. Interaction effect of irrigation and soil amendments of plant height during winter 2025–26

Treatments	60 DAS				90 DAS				At harvest			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	42.90	43.50	43.20	43.2	78.50	79.20	78.60	78.77	100.32	103.30	101.63	101.75
A ₂	46.91	51.61	43.89	47.47	82.40	91.90	79.60	84.63	105.73	115.59	103.60	108.31
A ₃	47.94	54.90	46.69	49.84	83.87	96.20	81.20	87.09	110.20	118.74	105.52	111.49
A ₄	45.60	50.79	49.20	48.53	79.90	89.98	87.40	85.76	105.31	115.07	110.67	110.35
A ₅	48.17	58.10	52.69	52.99	84.20	100.30	92.50	92.33	110.28	122.00	116.33	116.2
A ₆	50.45	59.90	53.41	54.59	89.60	100.90	94.20	94.9	110.94	124.99	116.40	117.44
A ₇	55.17	60.20	55.71	57.03	97.10	102.60	97.80	99.17	118.80	127.00	119.80	121.87
A ₈	55.86	62.81	56.89	58.52	99.20	103.90	99.60	100.9	120.44	127.88	121.96	123.43
Mean	49.13	55.23	50.21		86.85	95.62	88.86		110.25	119.32	111.99	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI	I	A	IxA	AxI
SEd	0.50	0.88	1.65	1.63	0.53	2.22	2.84	3.30	0.87	4.03	4.67	5.68
C.D	1.39	1.90	3.50	3.40	1.49	4.77	5.90	6.90	2.43	8.64	9.68	11.91

DAS: days after sowing.

Dry matter production (kg ha⁻¹)

With respect to the irrigation treatments, dry matter production (DMP) was significantly influenced by irrigation methods and soil amendment treatments during both seasons (Figs. 1 and 2). At 30 DAS, the drip irrigation system (I₁) recorded the highest DMP (2056 kg ha⁻¹), followed by soil moisture sensor-based irrigation (I₂) (1869 kg ha⁻¹), while the lowest DMP was observed under weather-based irrigation scheduling (I₃) (1800 kg ha⁻¹) during the summer season. Similar trends were recorded during the winter season.

At the later growth stages, significantly greater DMP was recorded under soil moisture sensor-based irrigation (I₂), which registered 4029, 7454 and 8602 kg ha⁻¹ at 60 DAS, 90 DAS and harvest, respectively. The lowest DMP values were recorded under drip irrigation alone (I₁), with values of 3615, 7017 and 7633 kg ha⁻¹ at the corresponding growth stages in the summer season. Similar trends were observed during the winter season.

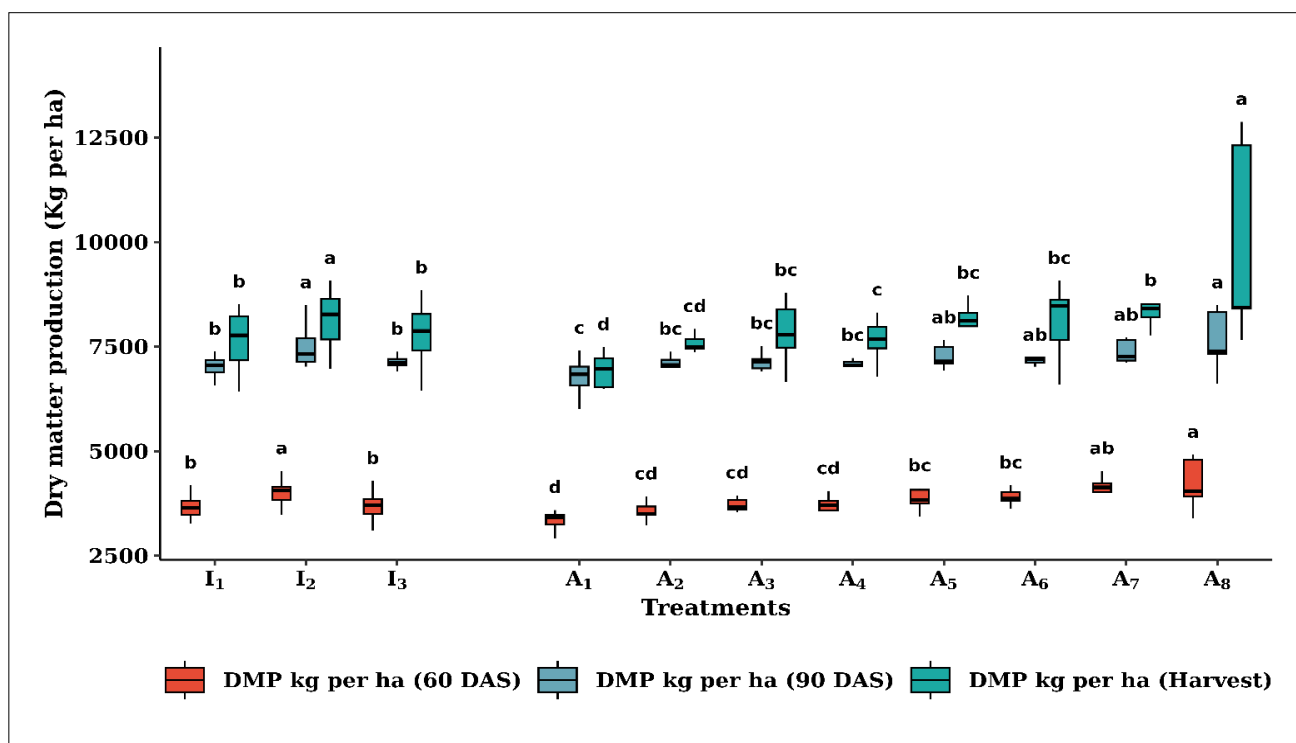


Fig. 1. Effect of irrigation and soil amendments on dry matter production (kg ha^{-1}) during summer 2025. DAS: days after sowing.

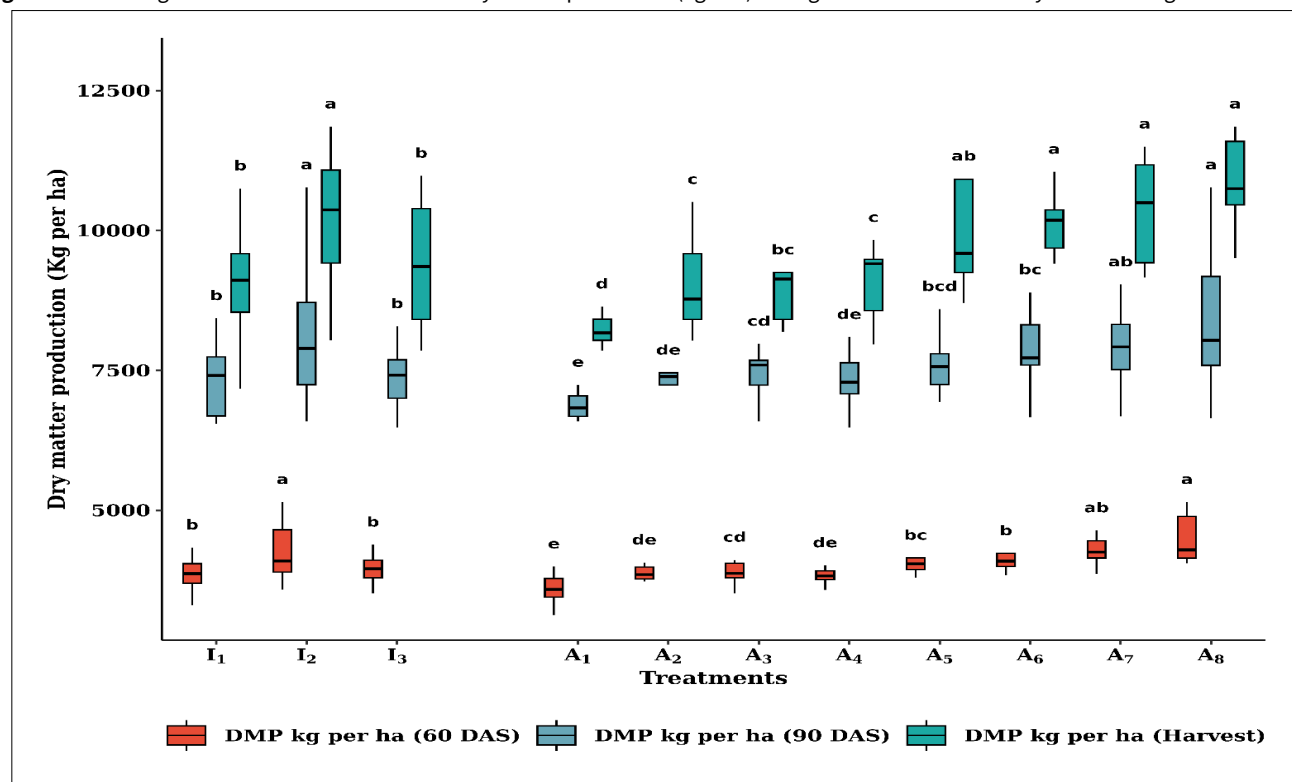


Fig. 2. Effect of irrigation and soil amendments on dry matter production (kg ha^{-1}) during winter 2025-26.

Among the soil amendment treatments, the application of liquid bio fertilisers (NFB, PSB and PMB, each at 5 L ha^{-1}) together with zeba at 12.5 kg ha^{-1} and EFYM at 7.5 t ha^{-1} (A_8) recorded significantly greater DMP values of 2199, 4225, 7641 and 9683 kg ha^{-1} at 30 DAS, 60 DAS, 90 DAS and harvest, respectively. This treatment was statistically comparable with the application of liquid bio fertilisers (NFB, PSB and PMB, each 5 L ha^{-1}) + zeba at 12.5 kg/ha as a basal application (A_7), which recorded DMP values of 2091, 4055, 7364 and 8269 kg ha^{-1} , respectively. The minimum DMP was observed under the untreated control (A_1), with values of 1691, 3351, 6753 and 6906 kg ha^{-1} at the respective growth stages during the summer season. Similar trends were observed during the winter season.

The interaction effects between irrigation and soil amendment treatments were non-significant at 30 DAS but significant at later growth stages. Among the treatment combinations, soil moisture sensor-based irrigation through a drip system coupled with the application of liquid bio fertilisers of NFB, PSB and PMB, each at 5 L ha^{-1} together with zeba at 12.5 kg ha^{-1} and EFYM at 7.5 t ha^{-1} (I_2A_8) recorded the greatest DMP of 4851, 8420 and 12574 kg ha^{-1} at 60 DAS, 90 DAS and harvest, respectively. In contrast, the minimum DMP was observed under drip irrigation with the untreated control (I_1A_1), which recorded DMP values of 3200, 6688 and 6541 kg ha^{-1} at the corresponding growth stages during the summer season. Similar results were obtained during the winter season.

Impact of treatments on yield attributes

The yield attributes, namely the number of sympodial branches and the number of bolls per plant, were significantly influenced by irrigation and soil amendment treatments, whereas the number of monopodial branches and boll weight remained statistically non-significant during both seasons.

Number of monopodial branches plant⁻¹

The number of monopodial branches plant⁻¹ was not significantly influenced by irrigation treatments, soil amendments, or their interactions during either season (Table 5).

Number of sympodial branches plant⁻¹

Among the irrigation treatments, soil moisture sensor-based irrigation (I₂) recorded significantly higher numbers of sympodial branches plant⁻¹, viz. 12.79, 19.59 and 28.33 at 60 DAS, 90 DAS and harvest, respectively. The lowest number of sympodial branches

was recorded under drip irrigation alone (I₁), which registered at 60 DAS, 90 DAS and harvest, respectively, 9.80, 17.65 and 25.75 during the summer season. Similar trends were observed during the winter season.

Among the soil amendment treatments, the application of liquid biofertilisers comprising NFB, PSB and PMB, each at 5 L ha⁻¹ along with zeba at 12.5 kg ha⁻¹ as a basal application and EFYM at 7.5 t ha⁻¹ (A₈), recorded the maximum number of sympodial branches plant⁻¹ (14.57, 20.70 and 30.15 at 60 DAS, 90 DAS and harvest, respectively), while the untreated control (A₁) recorded the minimum values (7.20, 14.95 and 22.44) during the summer season. Similar observations were made during the winter season (Table 6).

With respect to the interaction effects, the combination of soil moisture sensor-based irrigation through a drip system along with the application of liquid bio fertilisers comprising NFB, PSB and PMB, each at 5 L ha⁻¹ along with zeba at 12.5 kg ha⁻¹ and EFYM at

Table 5. Effect of irrigation and soil amendments on number of monopodial branches during summer 2025 and winter 2025–26

Treatments	Summer 2025			Winter 2025–26		
	60 DAS	90 DAS	At harvest	60 DAS	90 DAS	At harvest
I ₁	1.88	2.22	2.61	1.75	2.61	3.16
I ₂	0.95	1.44	1.96	1.37	1.84	2.42
I ₃	1.40	2.17	2.46	1.62	2.25	2.92
SEd	0.26	0.25	0.19	0.13	0.20	0.20
CD	NS	NS	NS	NS	NS	NS
A ₁	2.39	2.70	3.17	2.44	3.00	3.00
A ₂	1.74	2.46	2.69	2.03	2.68	2.68
A ₃	1.5	2.00	2.35	1.58	2.4	2.4
A ₄	1.86	2.38	2.63	1.81	2.39	2.39
A ₅	1.29	1.81	2.16	1.46	1.92	1.92
A ₆	1.24	1.44	1.86	1.34	2.11	2.11
A ₇	0.71	1.58	2.23	0.91	1.76	1.76
A ₈	0.59	1.18	1.65	1.03	1.62	1.62
SEd	0.59	0.57	0.47	0.50	0.42	0.53
CD	NS	NS	NS	NS	NS	NS
Irrigation x Soil amendments						
SEd	0.76	0.76	0.71	0.45	0.51	0.57
CD	NS	NS	NS	NS	NS	NS
Soil amendments x Irrigation						
SEd	0.86	0.85	0.76	0.62	0.58	0.71
CD	NS	NS	NS	NS	NS	NS

DAS: days after sowing.

Table 6. Effect of irrigation and soil amendments of number of sympodial branches during summer 2025 and winter 2025–26

Treatments	Summer 2025			Winter 2025–26		
	60 DAS	90 DAS	At harvest	60 DAS	90 DAS	At harvest
I ₁	9.80	17.65	25.75	9.12	15.72	23.54
I ₂	12.79	19.59	28.33	12.12	18.27	26.63
I ₃	10.53	18.06	26.25	9.81	16.13	24.28
SEd	0.16	0.31	0.50	0.20	0.12	0.27
CD	0.44	0.88	1.40	0.57	0.34	0.76
A ₁	7.20	14.95	22.44	6.50	13.14	20.33
A ₂	9.37	17.50	25.11	8.56	15.32	22.89
A ₃	10.13	18.04	26.00	9.48	15.92	23.67
A ₄	9.77	17.72	26.44	8.70	15.48	23.19
A ₅	11.73	19.27	27.53	11.27	17.47	25.75
A ₆	12.23	19.36	28.11	11.68	17.91	26.23
A ₇	13.30	19.95	29.24	12.89	18.85	27.67
A ₈	14.57	20.70	30.15	15.24	19.56	28.78
SEd	0.22	0.62	0.26	0.28	0.43	0.40
CD	0.47	1.34	0.56	0.60	0.94	0.86
Irrigation x Soil amendments						
SEd	0.47	0.85	1.02	0.40	0.47	0.80
CD	1.00	1.83	2.27	0.90	0.98	1.72
Soil amendments x Irrigation						
SEd	0.44	0.93	0.82	0.41	0.59	0.77
CD	0.92	1.95	1.68	0.86	1.24	1.61

DAS: days after sowing.

7.5 t ha⁻¹ (I₂A₈) recorded the highest number of sympodial branches plant⁻¹ (16.91, 22.11 and 32.11 at 60 DAS, 90 DAS and harvest, respectively), whereas the lowest values were observed under drip irrigation with control (I₁A₁) (6.50, 13.71 and 22.00 at 60 DAS, 90 DAS and harvest, respectively) during the summer season. Similar trends were observed during the winter season (Tables 7 and 8).

Number of bolls plant⁻¹

Among irrigation treatments, soil moisture sensor-based irrigation (I₂) significantly produced the highest number of bolls plant⁻¹ (10.99), whereas the lowest number was observed under drip irrigation alone

(I₁) with 9.34 at harvest stage during the summer season. Similar results were recorded during the winter season (Table 9).

Among the soil amendment treatments, application of liquid bio fertilisers comprising NFB, PSB and PMB each at 5 L ha⁻¹, along with zeba at 12.5 kg ha⁻¹ as a basal application and EFYM at 7.5 t ha⁻¹ (A₈), recorded significantly higher numbers of bolls plant⁻¹ (12.00), while the untreated control (A₁) recorded the lowest value (8.17) at the harvest stage during the summer season. Similar observations were made during the winter season.

Table 7. Interaction effect of irrigation and soil amendments of number of sympodial branches during summer 2025

Treatments	60 DAS				90 DAS				At Harvest			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	6.50	7.60	7.50	7.20	13.71	15.73	15.40	14.95	22.00	23.00	22.33	22.44
A ₂	8.70	11.00	8.40	9.37	17.45	19.03	16.03	17.50	25.00	27.00	23.33	25.11
A ₃	9.40	12.10	8.90	10.13	17.82	19.27	17.02	18.04	25.00	28.67	24.33	26.00
A ₄	8.80	10.70	9.80	9.77	16.81	18.25	18.11	17.72	24.00	29.33	26.00	26.44
A ₅	9.50	14.00	11.70	11.73	18.04	20.7	19.08	19.27	26.00	29.60	27.00	27.53
A ₆	10.10	14.80	11.80	12.23	18.19	20.78	19.11	19.36	26.33	30.00	28.00	28.11
A ₇	12.20	15.21	12.50	13.30	19.35	20.88	19.61	19.95	28.33	31.00	28.40	29.24
A ₈	13.20	16.91	13.60	14.57	19.87	22.11	20.11	20.70	29.33	32.11	29.00	30.15
Mean	9.80	12.79	10.53		17.65	19.59	18.06		25.75	28.84	26.05	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI	I	A	IxA	AxI
SEd	0.16	0.22	0.47	0.44	0.31	0.62	0.85	0.93	0.50	0.26	1.02	0.82
C.D	0.44	0.47	1.00	0.92	0.88	1.34	1.83	1.95	1.40	0.56	2.27	1.68

DAS: days after sowing.

Table 8. Interaction effect of irrigation and soil amendments of number of sympodial branches plant during winter 2025–26

Treatments	60 DAS				90 DAS				At Harvest			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	5.85	6.95	6.70	6.50	12.96	13.46	13.00	13.14	19.50	20.96	20.52	20.33
A ₂	8.11	10.46	7.11	8.56	15.00	16.99	13.96	15.32	22.14	24.85	21.68	22.89
A ₃	8.54	11.87	8.03	9.48	15.24	17.89	14.63	15.92	23.01	26.00	22.00	23.67
A ₄	7.56	9.55	9.00	8.70	14.32	16.51	15.62	15.48	21.87	24.00	23.71	23.19
A ₅	8.72	13.95	11.14	11.27	15.49	19.74	17.18	17.47	23.19	28.75	25.32	25.75
A ₆	9.32	14.28	11.44	11.68	16.18	20.10	17.46	17.91	23.95	29.00	25.75	26.23
A ₇	12.00	14.66	12.01	12.89	18.04	20.44	18.07	18.85	26.85	29.04	27.13	27.67
A ₈	12.85	15.24	13.01	13.70	18.56	21.01	19.12	19.56	27.82	30.40	28.11	28.78
Mean	9.12	12.12	9.81		15.72	18.27	16.13		23.54	26.63	24.28	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI	I	A	IxA	AxI
SEd	0.20	0.28	0.40	0.41	0.12	0.43	0.47	0.59	0.27	0.40	0.80	0.77
C.D	0.57	0.60	0.90	0.86	0.34	0.94	0.98	1.24	0.76	0.86	1.72	1.61

DAS: days after sowing.

Table 9. Effect of irrigation and soil amendments on no of bolls plant⁻¹, boll weight (g) and seed cotton yield (kg ha⁻¹) during summer 2025 and winter 2025–26

Treatments	Summer 2025			Winter 2025–26		
	Number of bolls	Boll weight (g)	Seed cotton yield (Kg ha ⁻¹)	Number of bolls	Boll weight (g)	Seed cotton yield (Kg ha ⁻¹)
I ₁	9.34	3.72	2523	8.64	3.64	2335
I ₂	10.99	4.19	2936	10.78	3.61	2880
I ₃	9.56	4.29	2579	9.38	3.64	2537
SEd	0.28	0.09	86	0.13	0.07	39
CD	0.80	NS	240	0.37	NS	109
A ₁	8.17	3.76	2199	6.73	3.53	1776
A ₂	9.13	3.99	2479	8.87	3.67	2417
A ₃	9.30	3.86	2524	9.03	3.67	2473
A ₄	9.17	3.65	2480	9.03	3.67	2455
A ₅	10.2	5.05	2744	10.03	3.64	2704
A ₆	10.47	3.62	2800	10.33	3.62	2767
A ₇	11.27	3.61	3012	11.07	3.62	2964
A ₈	12.00	5.00	3200	11.67	3.61	3115
SEd	0.25	0.10	95	0.27	1.16	73
CD	0.55	NS	205	0.58	NS	157
Irrigation x Soil amendments						
SEd	0.61	0.23	157	0.46	0.22	147
CD	1.35	NS	356	0.98	NS	310
Soil amendments x Irrigation						
SEd	0.53	0.21	149	0.47	0.24	144
CD	1.11	NS	311	0.99	NS	299

The interaction treatment involving soil moisture sensor-based irrigation through a drip system along with application of liquid bio fertilisers containing NFB, PSB and PMB each at 5 L ha⁻¹ together with zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹ (I₂A₈), recorded the highest number of bolls plant⁻¹ (14.0), whereas the lowest number was recorded under drip irrigation with the untreated control (I₁A₁) (8.0) at the harvest stage during the summer season. Similar trends were observed during the winter season (Table 10).

Boll weight (g)

Boll weight was not significantly influenced by irrigation treatments, soil amendments, or their interactions during either seasons (Table 9).

Seed cotton yield (kg ha⁻¹)

Seed cotton yield was significantly influenced by smart irrigation techniques and soil amendment treatments during both seasons (Fig. 3). Among the irrigation treatments, soil moisture sensor-based irrigation (I₂) recorded significantly higher seed cotton yields of 2936 and 2880 kg ha⁻¹ during the summer and winter seasons, respectively. The lowest yield was recorded under drip irrigation alone (I₁), which produced 2523 and 2335 kg ha⁻¹ during the summer and winter seasons, respectively (Table 9).

Among the soil amendment treatments, application of liquid bio fertilisers comprising NFB, PSB and PMB, each at 5 L ha⁻¹ along with zeba at 12.5 kg ha⁻¹ as a basal application and EFYM at 7.5 t ha⁻¹ (A₈), recorded significantly higher seed cotton yields of 3200 and

Table 10. Interaction effect of irrigation and soil amendments of number of bolls per plant during summer 2025 and winter 2025–26

Treatments	Summer 2025				Winter 2025–26			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	8.0	8.3	8.2	8.17	4.0	8.2	8.0	6.73
A ₂	9.0	10.0	8.4	9.13	8.5	9.8	8.3	8.87
A ₃	9.2	10.2	8.5	9.30	8.8	10.0	8.3	9.03
A ₄	8.5	9.6	9.4	9.17	8.4	9.5	9.2	9.03
A ₅	9.0	11.5	10.1	10.2	9.0	11.3	9.8	10.03
A ₆	9.5	11.8	10.1	10.47	9.3	11.7	10.0	10.33
A ₇	10.5	12.5	10.8	11.27	10.4	12.2	10.6	11.07
A ₈	11.0	14.0	11.0	12.00	10.7	13.5	10.8	11.67
Mean	9.34	10.99	9.96		8.64	10.78	9.38	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI
SEd	0.28	0.25	0.61	0.53	0.13	0.27	0.46	0.47
C.D	0.80	0.55	1.35	1.11	0.37	0.58	0.98	0.99

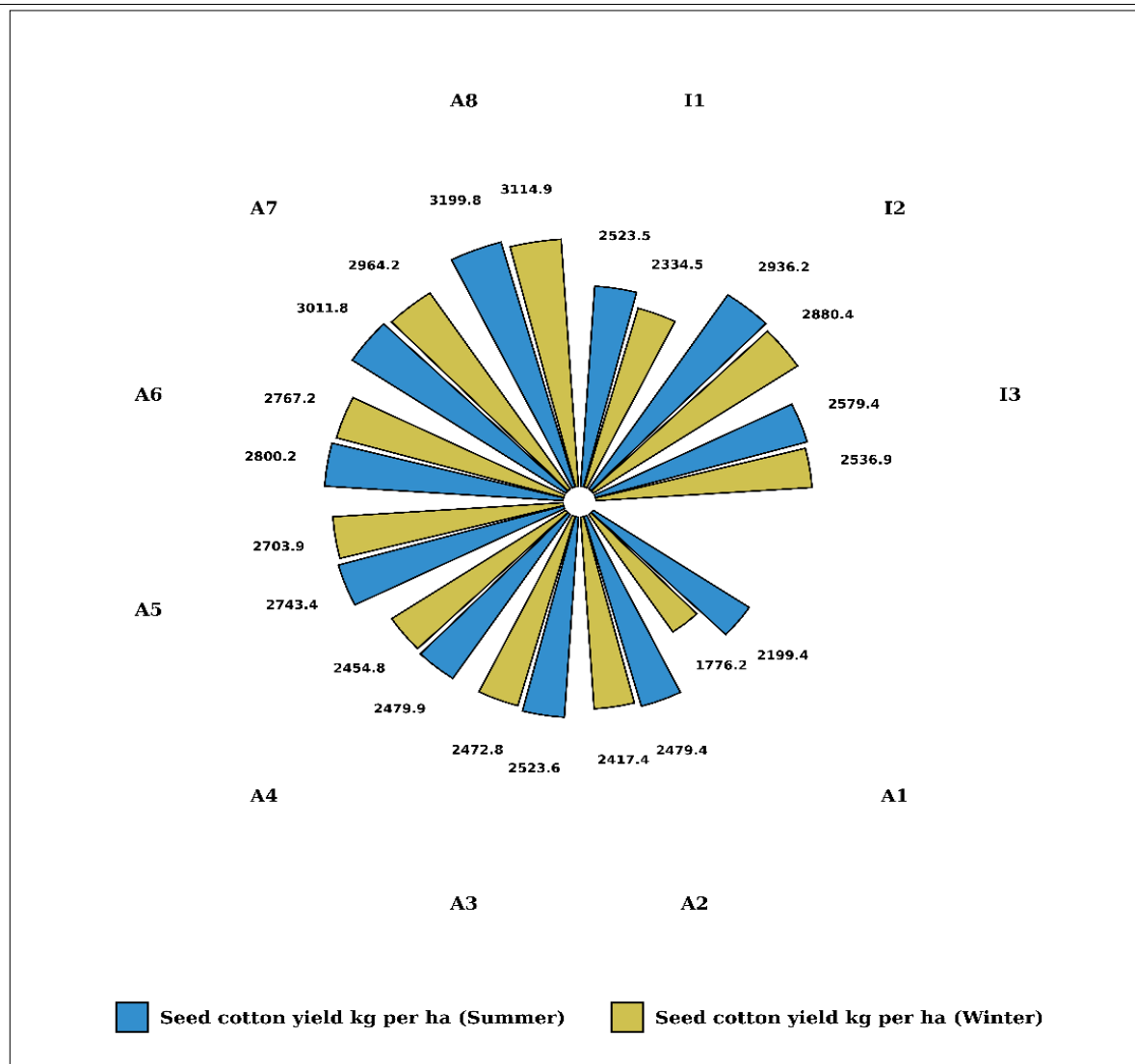


Fig. 3. Effect of irrigation and soil amendments on seed cotton yield (kg ha⁻¹) during summer 2025 and winter 2025-26.

3115 kg ha⁻¹ during the summer and winter seasons, respectively and was statistically on par with the application of liquid bio fertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹) along with zeba at 12.5 kg ha⁻¹ as a basal application (A₇). The lowest yield was recorded under the untreated control (A₁).

Regarding the interaction effects, the treatment combination involving soil moisture sensor-based irrigation through a drip system along with application of liquid bio fertilisers containing NFB, PSB and PMB, each at 5 L ha⁻¹ together with zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹ (I₂A₈), recorded significantly higher seed cotton yields of 3728 and 3571 kg ha⁻¹ during the summer and winter seasons, respectively. The lowest yield was recorded under drip irrigation with the untreated control (I₁A₁), with yields of 2108 and 1010 kg ha⁻¹ during the summer and winter seasons, respectively (Table 11).

Discussion

Impact of treatments on growth attributes

Plant height is an important morphological trait that determines canopy architecture and provides the structural framework for the development of fruiting branches and reproductive sinks, thereby contributing substantially to cotton productivity. In the present investigation, plant height increased progressively from the early vegetative growth to harvest, indicating the efficient utilisation of available resources under favourable moisture and nutrient conditions.

Among the irrigation treatments, soil moisture sensor-based irrigation through a drip system, based on a real-time soil moisture data, significantly enhanced plant height at all later growth stages compared with the drip irrigation system and weather-based irrigation. During the summer season, soil moisture sensor-based irrigation recorded plant heights of 53.82, 94.47 and 117.51 cm at 60 DAS, 90 DAS and harvest, respectively, representing increases of 13.2, 9.9 and 6.8 per cent over the drip irrigation system. Similarly, during the winter season, the same treatment recorded 55.23, 95.62 and 119.32 cm at the corresponding growth stages, which were 12.4, 10.1 and 8.2 per cent higher than those recorded under the drip irrigation system. The improvement in plant height under sensor-based irrigation may be attributed to the maintenance of optimum soil moisture throughout the crop growth period, which enhanced nutrient solubility, nutrient uptake and translocation of photosynthates. The continuous availability of moisture in the rhizosphere likely improved stomatal conductance, cell elongation and photosynthetic efficiency, thereby promoting vigorous vegetative growth and biomass accumulation. Similar findings of greater plant height, leaf area index and biomass production under automated irrigation systems in cotton were reported (5, 15).

Among the soil amendment treatments, the application of liquid biofertilisers comprising NFB, PSB and PMB, each at 5 L ha⁻¹, together with zeba at 12.5 kg ha⁻¹ as a basal application and EFYM at 7.5 t ha⁻¹ (A₈), significantly increased plant height over the untreated control. During the summer season, this treatment recorded plant heights of 23.79, 56.56, 99.26 and 122.13 cm at 30 DAS, 60 DAS, 90 DAS and harvest, respectively, representing increases of 113.0, 37.0, 26.6 and 19.3 % over the control. The treatment was statistically on par with the application of liquid bio fertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹) together with zeba at 12.5 kg ha⁻¹ as a basal application, which recorded plant heights of 22.56, 55.63, 97.80 and 120.14 cm, respectively. Similar improvements were observed during the winter season, in which the integrated application of liquid bio fertilisers, zeba and EFYM recorded increases of 106.2, 35.5, 28.1 and 21.3 % over the control at the corresponding growth stages. The enhanced growth under integrated amendment treatments may be attributed to improved nutrient mineralisation, enhanced microbial activity, increased nutrient availability and improved soil moisture retention. Bio fertilisers facilitated biological nitrogen fixation, phosphorus solubilisation and potassium mobilisation, while EFYM improved soil structure, microbial population and nutrient-buffering capacity. Zeba hydrogel further enhanced soil moisture conservation and minimised moisture stress under field conditions. Similar observations of a 15.8–21.4 % increase in plant height with bio fertilisers and organic amendments and a maximum plant height of 122.4 cm under integrated nutrient management, were reported (16, 17). A 32–45 % increase in soil moisture retention with the application of a superabsorbent polymer, which contributed to improved crop growth, was also reported (18).

The interaction effect between irrigation and soil amendments further demonstrated the synergistic influence of precision irrigation and integrated nutrient management on cotton growth. The combination of soil moisture sensor-based irrigation on a real-time basis through a drip system using soil moisture data, along with the application of liquid biofertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹), zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹, recorded the greatest plant height during both seasons. In the summer season, this treatment combination recorded plant heights of 61.20, 101.05 and 124.26 cm at 60 DAS, 90 DAS and harvest, respectively, representing increases of 54.2, 29.0 and 21.0 per cent over the drip irrigation system under control conditions. Likewise, during the winter season, the same combination recorded plant heights of 62.8, 103.9 and 127.88 cm, which were 46.4, 32.2 and 27.5 % higher than those under the drip irrigation system with the control treatment at the corresponding stages. The superior performance of this integrated treatment combination may be attributed to the continuous maintenance of optimum soil moisture, coupled with enhanced

Table 11. Interaction effect of irrigation and soil amendments of seed cotton yield (kg ha⁻¹)

Treatments	Summer 2025				Winter 2025–26			
	I ₁	I ₂	I ₃	Mean	I ₁	I ₂	I ₃	Mean
A ₁	2108	2252	2238	2199	1010	2220	2099	1776
A ₂	2466	2678	2294	2479	2327	2630	2295	2417
A ₃	2502	2753	2316	2524	2405	2690	2323	2473
A ₄	2314	2588	2538	2480	2299	2564	2502	2455
A ₅	2466	3060	2705	2744	2446	3022	2644	2704
A ₆	2568	3123	2709	2800	2516	3104	2681	2767
A ₇	2833	3308	2895	3012	2798	3241	2853	2964
A ₈	2932	3728	2939	3200	2876	3571	2898	3115
Mean	2523	2936	2579		2335	2880	2537	
Interaction	I	A	IxA	AxI	I	A	IxA	AxI
SEd	86	96	157	149	39	73	148	144
C.D	240	205	357	312	109	157	310	299

nutrient availability and microbial activity, which collectively improved root growth, assimilate partitioning and overall crop vigour.

Dry matter production followed trends like those observed for plant height. Soil moisture sensor-based irrigation on a real-time basis through a drip system using soil moisture data recorded significantly greater dry matter accumulation at the later growth stages. During the summer season, this treatment produced 4029, 7454 and 8602 kg ha⁻¹ at 60 DAS, 90 DAS and harvest, respectively, which were 11.5, 6.2 and 12.7 per cent higher than those recorded under the drip irrigation system. Improved dry matter production under sensor-based irrigation may be attributed to uninterrupted moisture availability and enhanced nutrient uptake, which promoted photosynthetic activity and assimilate accumulation. Similar findings of a 26.5 % higher total dry matter accumulation and 33.4 % greater leaf biomass under optimised irrigation management compared with reduced irrigation, with the increase attributed to improved photosynthetic activity and resource utilisation, were reported (19).

Among the soil amendment treatments, the application of liquid bio fertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹) together with zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹ recorded significantly greater dry matter production, with increases of 30.0, 26.1, 13.1 and 40.2 % over the untreated control at 30 DAS, 60 DAS, 90 DAS and harvest, respectively, during the summer season. This treatment was closely followed by the application of liquid biofertilisers together with zeba. Enhanced dry matter accumulation under integrated amendments might be attributed to better root proliferation, increased microbial activity and improved nutrient-use efficiency. The integrated application of FYM and fertilisers increased seed cotton yield from 1.94–2.33 t ha⁻¹ compared with fertiliser alone, indicating greater biomass production and improved nutrient utilisation under integrated nutrient management (20).

The interaction combination involving soil moisture sensor-based irrigation together with the application of liquid bio fertilisers, zeba and EFYM recorded the maximum dry matter production of 4851, 8420 and 12574 kg ha⁻¹ at 60 DAS, 90 DAS and harvest, respectively, which were 51.6, 25.9 and 92.2 % higher than those recorded under the drip irrigation system with the control treatment. This clearly indicated the beneficial synergistic effect of sensor-based irrigation and integrated organic amendments on biomass accumulation and crop growth.

Greater plant height and dry matter production observed during the winter season compared with the summer season may be attributed to relatively favourable environmental conditions, such as moderate temperatures and higher relative humidity, which enhanced photosynthetic efficiency and assimilate partitioning. Similar seasonal responses were previously reported (21, 22).

Impact of treatments on yield attributes

The yield attributes, particularly the number of sympodial branches and bolls per plant, were significantly influenced by irrigation scheduling and soil amendment treatments. Sympodial branches are directly associated with reproductive development and boll-bearing capacity of cotton.

Among the irrigation treatments, soil moisture sensor-based irrigation on a real-time basis through a drip system using soil moisture data recorded significantly higher numbers of sympodial branches per plant. During the summer season, this treatment recorded 12.79, 19.59 and 28.33 branches per plant at 60 DAS, 90

DAS and harvest, respectively, which were 30.5, 11.0 and 10.0 per cent higher than those recorded under the drip irrigation system. Similarly, during the winter season, the treatment recorded increases of 32.9, 16.2 and 13.1 per cent over the drip irrigation system at the corresponding stages. Likewise, 18.03 and 19.06 sympodial branches per plant were recorded during the 2023 and 2024 growing seasons, respectively, under automated sensor-based irrigation, compared with 15.62 and 16.48 branches per plant under conventional irrigation, indicating the beneficial effect of maintaining optimum root-zone moisture on fruiting branch development (7). Continuous soil moisture availability under sensor-based irrigation likely improved nutrient uptake and reduced flower and square shedding, thereby promoting the formation and retention of fruiting branches.

Among the soil amendment treatments, the application of liquid bio fertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹) together with zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹ recorded significantly higher numbers of sympodial branches per plant, with increases of 102.4, 38.5 and 34.4 % over the untreated control during the summer season. This treatment was closely followed by the application of liquid bio fertilisers together with zeba. Similar trends were observed during the winter season, where the integrated application of bio fertilisers, zeba and EFYM recorded increases of 134.5, 48.9 and 41.6 per cent over the control at the corresponding stages. Similar findings were reported, with the application of FYM at 30 t ha⁻¹ increased dry matter accumulation to 306.1 g plant⁻¹, sympodial branches to 35.2 plant⁻¹ and seed cotton yield to 36.8 q ha⁻¹ compared with the control, owing to improved nutrient availability and soil biological activity (23). Enhanced nutrient availability and improved microbial activity under integrated amendments might have stimulated meristematic activity and reproductive differentiation, resulting in increased formation of fruiting branches.

The combination of soil moisture sensor-based irrigation together with the application of liquid bio fertilisers, zeba and EFYM recorded the highest number of sympodial branches per plant during both seasons, indicating the synergistic effect of precise moisture management and integrated nutrient supply on reproductive growth. During the summer season, this treatment recorded 16.91, 22.11 and 32.11 branches per plant at 60 DAS, 90 DAS and harvest, respectively, representing increases of 160.2, 61.0 and 45.9 % over the drip irrigation system with the control treatment. A similar trend was observed during the winter season, when the same treatment consistently maintained a greater number of sympodial branches than the other treatment combinations, highlighting the beneficial influence of continuous soil moisture availability, enhanced nutrient uptake and improved assimilate partitioning on fruiting branch development and retention.

The number of bolls per plant also increased significantly under sensor-based irrigation and integrated soil amendment treatments. Soil moisture sensor-based irrigation on a real-time basis through a drip system using soil moisture data recorded 10.99 and 10.78 bolls per plant during the summer and winter seasons, respectively, which were 17.7 and 24.8 per cent higher than those recorded under the drip irrigation system. Among the soil amendment treatments, the application of liquid bio fertilisers together with zeba and EFYM recorded 12.00 and 11.67 bolls per plant during the summer and winter seasons, respectively, representing increases of 46.9 and 73.4 per cent over the untreated control.

The interaction treatment involving soil moisture sensor-based irrigation together with liquid biofertilisers, zeba and EFYM recorded the highest number of bolls per plant (14.0 and 13.5 during the summer and winter seasons, respectively), which were 75.0 and 237.5 per cent higher than those recorded under the drip irrigation system with the control treatment. The increase in the number of bolls under precision irrigation and integrated amendments may be attributed to reduced reproductive shedding, enhanced assimilate translocation and improved sink strength during the flowering and boll development stages. Similar findings were previously reported (24, 25, 9).

However, the number of monopodial branches and boll weight were not significantly influenced by irrigation or soil amendment treatments during either season. This may be due to the strong genetic regulation of these traits in Bt cotton hybrids, in which environmental and management interventions exert relatively limited influence (26).

Impact of treatments on seed cotton yield

Seed cotton yield is a complex trait governed by the interaction of growth parameters, assimilate partitioning, nutrient uptake and environmental conditions. In the present study, soil moisture sensor-based irrigation on a real-time basis through a drip system using soil moisture data significantly enhanced seed cotton yield over the other irrigation treatments. During the summer season, this treatment recorded a seed cotton yield of 2936 kg ha⁻¹, which was 16.4 % higher than drip irrigation system and 13.8 % higher than weather-based irrigation. Similarly, during the winter season, the treatment recorded a seed cotton yield of 2880 kg ha⁻¹, representing increases of 23.3 and 13.5 % over the drip irrigation system and weather-based irrigation, respectively. The improvement in yield under sensor-based irrigation may be attributed to precise irrigation scheduling, which maintained optimum soil moisture in the root zone and improved nutrient-use efficiency throughout the crop growth period. Similar findings were reported with a 9–13 % increase in cotton lint yield under sensor-based irrigation scheduling compared with conventional irrigation practices (27). Real-time irrigation scheduling improved seed cotton yield by 14.2 % and water-use efficiency by 18.7 % compared with farmer's irrigation practice (28). Likewise, a significantly higher seed cotton yield (2857 kg ha⁻¹) was recorded under precision water and nutrient management than under conventional management (2428 kg ha⁻¹), with the increase attributed to improved soil moisture availability and nutrient uptake (29).

Among the soil amendment treatments, the application of liquid biofertilisers (NFB, PSB and PMB, each at 5 L ha⁻¹) together with zeba at 12.5 kg ha⁻¹ and EFYM at 7.5 t ha⁻¹ recorded significantly higher seed cotton yields of 3200 and 3115 kg ha⁻¹ during the summer and winter seasons, respectively, representing increases of 45.5 and 75.4 % over the untreated control. The treatment was statistically comparable with the application of liquid bio fertilisers together with zeba, which recorded seed cotton yields of 3012 and 2964 kg ha⁻¹ during the respective seasons. The enhanced yield under integrated amendments may be attributed to improved soil fertility, microbial activity, nutrient availability and moisture conservation. Integrated application of bio fertilisers with organic and inorganic nutrient sources increased seed cotton yield from 247.60–607.68 kg ha⁻¹ and cotton stalk yield from 474.22 to 1198.13 kg ha⁻¹ compared with the control, demonstrating the beneficial effects of enhanced nutrient availability and biological activity on cotton productivity (28).

The interaction treatment involving soil moisture sensor-based irrigation together with the application of liquid bio fertilisers, zeba and EFYM recorded the highest seed cotton yields of 3728 and 3571 kg ha⁻¹ during the summer and winter seasons, respectively, representing increases of 76.9 and 253.6 per cent over the drip irrigation system under control conditions. The superior performance of this integrated treatment clearly demonstrated the synergistic effects of precision irrigation, biofertilisers, EFYM and zeba hydrogel in enhancing crop growth, reproductive efficiency and assimilate translocation to developing bolls. Zeba hydrogel likely minimised moisture stress during critical growth stages by gradually releasing stored water into the rhizosphere, thereby supporting sustained crop growth and productivity. Similar findings have been reported previously (13, 30).

Conclusion

The integration of smart irrigation and soil health management practices significantly enhanced the growth, yield attributes and productivity of *Bacillus thuringiensis* (Bt) cotton. Soil moisture sensor-based irrigation on a real-time basis through a drip system moisture data consistently recorded superior plant height, dry matter production, number of sympodial branches and seed cotton yield compared with conventional drip irrigation and weather-based irrigation, owing to optimum soil moisture maintenance and improved nutrient uptake. Among the soil amendment treatments, the application of liquid bio fertilisers comprising nitrogen-fixing bacteria (NFB), phosphate-solubilising bacteria (PSB) and potassium-mobilising bacteria (PMB), each at 5 L ha⁻¹, along with zeba at 12.5 kg ha⁻¹ and enriched farmyard manure (EFYM) at 7.5 t ha⁻¹ significantly improved crop growth and productivity through enhanced nutrient availability, microbial activity and soil moisture conservation. The interaction of sensor-based irrigation with the integrated application of bio fertilisers, zeba and EFYM recorded the highest growth, yield attributes and seed cotton yield during both seasons, demonstrating the synergistic benefits of precision irrigation and integrated nutrient management. Therefore, the combined use of soil moisture sensor-based irrigation, biofertilisers, zeba and EFYM can be recommended as a sustainable strategy for improving cotton productivity, water-use efficiency and soil health in Tamil Nadu. However, the higher initial cost of sensor-based irrigation systems may require subsidy support to facilitate wider adoption. Future research should focus on the long-term economic feasibility and validation of this technology under diverse agro-climatic conditions.

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Authors' contributions

KV conceptualised and wrote the original draft. RM conceptualised, supervised and reviewed the writing and editing. KR, SS, BK and SC contributed to the review of the manuscript. All authors read and approved the final manuscript.

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