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NITROGEN SCHEDULING FOR *BT*-COTTON HYBRIDS AND ITS EVALUATION USING CROPGRO-COTTON MODEL UNDER LIGHT TEXTURED SOILS OF SOUTH-WESTERN PUNJAB

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ABSTRACT

Nitrogen (N) availability is a critical factor influencing cotton yield and productivity. To evaluate the response of American cotton hybrids to split applications of nitrogen for enhanced productivity, field experiments were conducted during the *kharif* seasons of 2017 and 2018 at the Punjab Agricultural University (PAU)-Regional Research Station, Bathinda. The study aimed to assess the effects of various nitrogen application schedules on cotton yield. The experiment followed a split-plot design and was replicated three times. Three BG-II cotton hybrids *viz*., RCH 650 (V1), RCH 773 (V2), and NCS 855 (V3) were assigned to the main plots, while three nitrogen application schedules were tested in the sub-main plots: (1) ½ N at the 1st irrigation + ½ N at 50% flowering (N_1), (2) ¼ N at the 1st irrigation + ¼ N at the 2nd irrigation + ½ N at 50% flowering (N_2), and (3) ½ N at the 1st irrigation + ¼ N at the start of flowering + ¼ N at 50% flowering (N_3). The results indicated a significant increase in seed cotton yield under the N_3 schedule, followed by N_2, with the lowest yield observed under the N_1 schedule across both years. The highest seed cotton yield was recorded in the Bt hybrid RCH 773, followed by NCS 855. The yield reductions were 12.9% for RCH 650 and 5.9% for NCS 855 when compared to RCH 773. Regarding total crop water use, NCS 855 exhibited the highest water consumption, closely followed by RCH 773. In terms of nitrogen application schedules, N_3 resulted in the highest total crop water use, followed by N_1 and N_2. Water use efficiency was highest in RCH 650, followed by RCH 773 and NCS 855, with N_3 demonstrating the greatest water use efficiency overall. These findings highlight the importance of nitrogen application schedules in optimizing both cotton yield and water use efficiency, with the N_3 schedule showing the most promising results for enhancing productivity.

Keywords: Cotton productivity, CROPGRO-Cotton model, Split nitrogen application, Water use efficiency

Cotton, often referred to as 'white gold', is a vital fiber crop primarily cultivated for the textile industry. It is grown in numerous countries around the world, with India leading globally in cotton acreage. The country dedicates approximately 11.91 million hectares to cotton cultivation, which accounts for roughly 36% of the total global cotton area of 32.64 million hectares. In the 2021-22 season, India's cotton productivity reached approximately 445 kg per hectare. As one of the largest producers, consumers, and exporters of cotton, India plays a central role in the global cotton market. In Punjab, during the same period, American cotton was cultivated on 2,49,000 hectares, yielding a total production of 6,39,000 bales, with an average yield of 4.36 quintals of lint per hectare (Anonymous, 2023).

In the light-textured soils of southwestern Punjab, India, cotton cultivation is well-suited for the *kharif* season. Bathinda district, located in the semi-arid region of Punjab, has the highest acreage under cotton, ranging from 1,55,000 to 1,62,000 hectares. Cotton in this region is predominantly irrigated using surface irrigation methods. However, cotton growers in arid and semi-arid regions worldwide face significant challenges in improving nutrient and water use efficiency. Nitrogen (N) is the second most limiting factor in semi-arid cotton production, after water (Morrow and Krieg, 1990; Bronson *et al.*, 2006). Consequently, the primary constraints affecting cotton production are nitrogen fertility and water availability. Unlike other major field crops, the nitrogen requirements and utilization by cotton are complex (Gerik *et al.*, 1998). Cotton is a heavy feeder of nitrogen and other essential nutrients. In addition to the total amount of nitrogen, its application timing is crucial for optimal growth, higher yield, and improved quality. Applying all or excess nitrogen at once, without splitting the application, can lead to lower nitrogen use efficiency and environmental pollution through leaching or runoff, contaminating groundwater and surface water bodies. Nitrogen leaching, denitrification, ammonia volatilization, and mineralization/immobilization are processes that can rapidly alter the availability of

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nitrogen for plants (Lemon *et al.*, 2009). During the early growth stages, cotton requires minimal amounts of nitrogen (Lemon *et al.*, 2009). However, its nitrogen needs must be carefully managed through proper scheduling to ensure consistent nutrient supply and maximize yield. Research indicates that split nitrogen applications, where one-third to one-half of the nitrogen is applied preplant, and the remainder is side-dressed during the squaring stage, result in higher yields compared to a single application at sowing (Lemon *et al.*, 2009).

Crop growth and development are influenced by a variety of weather parameters, including solar radiation and temperature, as well as by management practices (Pal *et al.*, 2016). Furthermore, both seed-cotton yield and quality are significantly impacted by the availability of sufficient and balanced nutrients in the soil. Effective soil-test-based nutrient management (Goovaerts, 1998) has been shown to enhance seed-cotton yields, improve fiber quality, and increase both water and nutrient use efficiency. Crop production is thus primarily determined by the integrated interactions between soil conditions, weather patterns, and management practices. These complex relationships can be effectively quantified and predicted using a well-calibrated and validated crop simulation model.

The Decision Support System for Agrotechnology Transfer (DSSAT) is a comprehensive decision-making tool that incorporates crop system models, including the Crop Growth Model (CSM)-CROPGRO-Cotton. This model allows for the validation of crop model outputs and facilitates the comparison of simulated results with observed field data. The CSM-CROPGRO-Cotton model is particularly valuable for strategic decision-making in both dryland and irrigated conditions, as it simulates the growth and development of cotton under varying environmental and management scenarios (Hoogenboom *et al.*, 2010; Jones *et al.*, 2003). As one of the most widely used tools for simulating crop growth on a daily basis, the CROPGRO-Cotton model also enables detailed analysis of photosynthesis on an hourly basis. Keeping in view the extensive application of crop simulation models in agricultural research, this study was designed to enhance understanding of the performance of three Bt cotton hybrids under three different nitrogen management schedules. The primary objective was to apply the CROPGRO-Cotton model to identify the optimal nitrogen schedule for maximizing nitrogen use efficiency and, consequently, seed-cotton yield.

MATERIALS AND METHODS

Experimental site

A two-year field experiment was conducted at the research farm of Punjab Agricultural University Regional Station in Bathinda, India, during the *kharif* seasons of 2017 and 2018. The experimental site is located in the southwestern zone (IV) of Punjab, at a latitude of 30° 09' 36" N, longitude 74° 55' 28" E, and an elevation of 211 meters above mean sea level. Geologically, the area is part of the Indo-Gangetic alluvial plains, which are characterized by the uniform deposition of Pleistocene and Holocene alluvial materials from the rivers of the Indo-Gangetic system. The region faces a scarcity of high-quality canal water, as the study area lies at the tail end of the canal network. Furthermore, the available groundwater is of poor quality, being either saline, sodic, or saline-sodic in nature.

Soil of experimental field

The zone is characterized by soils with a coarser texture, ranging from loamy sand to sandy loam. These soils exhibit an alkaline reaction, with a pH of 8.36, and belong to the Gehri Bhagi soil series (mixed, hyperthermic, Ustochreptic Camborthid). At the start of the experiment, the organic carbon content in the surface layer (0–15 cm) of the soil was 2.2 g kg^{-1}. The available nutrients in the surface layer were as follows: nitrogen (N) 128.7 kg ha^{-1}, phosphorus (P) 13.5 kg ha^{-1}, and potash (K) 336 kg ha^{-1} (Table 1). The soil had no salinity, with an electrical conductivity (EC) of 0.16 dS m^{-1}, and the water table was approximately 8 meters deep.

Table 1. Initial physico-chemical characteristics of soil (0-15 cm)

Parameter	Particulars
Soil texture	Loamy sand
Sand (%)	79.9
Silt (%)	11.9
Clay (%)	8.2
pH	8.31
EC (dS m^{-1})	0.16
$CaCO_3$ (%)	4.45
Organic carbon (%)	0.21
Available N (kg ha^{-1})	128.7
Available P (kg ha^{-1})	13.5
Available K (kg ha^{-1})	334
Bulk density (g cm^{-3})	1.56
Field capacity moisture (cm)	3.11
Permanent wilting point moisture (cm)	0.77

Experimental treatments and procedures

The study compared three American cotton hybrids under three nitrogen (N) scheduling treatments, with the aim of optimizing productivity. The experiment was conducted in a split-plot design, replicated thrice. The BG-II cotton hybrids *viz.* RCH 650 (V_1), RCH 773 (V_2), and NCS 855 (V_3) were assigned to the main plots. Three nitrogen scheduling treatments were applied in the sub-main plots: ½ N at the first irrigation + ½ N at 50% flowering (N_1); ¼ N at the first irrigation + ¼ N at the second irrigation + ½ N at 50% flowering (N_2); and ½ N at the first irrigation + ¼ N at the start of flowering + ¼ N at 50% flowering (N_3). For nitrogen top-dressing, 50% of the plants showing flower buds were visually identified, and nitrogen was applied according to the specific treatment. Prior to sowing, cotton seeds were soaked in water for 2-4 hours to enhance seedling establishment, promote initial growth, and increase yields. Cotton was sown in rows 67.5 cm apart, with a plant-to-plant spacing of 75 cm, using the dibbling method during the first week of May in both years. To control weed infestation, three hoeings were performed: the first before the first irrigation, the second at 60 days after sowing (DAS), and the third at 75 DAS. The recommended fertilizers for optimal crop growth included 105 kg N, 30 kg P_2O_5 (DAP), and 16 kg zinc sulfate monohydrate (33%) per hectare. Additionally, four foliar sprays of 2% potassium nitrate (13:0:45) were applied at weekly intervals starting at flower initiation. A total of five irrigations, each 7.5 cm in depth, were applied, with the first irrigation given four weeks after sowing. Cotton was harvested in two pickings, at 15-20 days interval, to minimize fiber quality loss, as delayed picking can adversely affect fiber strength.

Total water use efficiency

Total Water Use Efficiency (TWUE) was calculated by assessing the total crop water use for each treatment. Total crop water use is the sum of the irrigation water applied, profile water used, and rainfall received during the growing season (Sandhu *et al.*, 1992). Irrigation water, profile water, and rainfall events were recorded throughout the duration of the experiment. Profile water use was measured in the 0 to 180 cm soil profile depth using the gravimetric method for both years of the study. To calculate TWUE, the seed cotton yield (in kg per hectare) was divided by the total water use, and the result was expressed as kg per millimeter (kg mm^{-1}).

Soil analysis

Upon completion of the experiment, soil samples were collected using a soil auger from both the surface (0-15 cm) and sub-surface (15-30 cm) layers to assess the chemical properties of the soil. The samples were air-dried in the shade, sieved through a 2 mm mesh, and stored in cloth bags for further analysis. The soil was then analyzed for several chemical properties, including pH (measured using a 1:2 soil-to-water ratio), electrical conductivity (measured using a 1:2 soil-to-water ratio with a conductivity bridge), organic carbon (determined by the oxidation method), available nitrogen (measured using the Kjeldahl method), available phosphorus (extracted using $NaHCO_3$), and available potassium (extracted using NH_4OAC).

Agrometeorological observations

Weather data during the study period were recorded from the agro-meteorological observatory of the University, located approximately 20 meters from the experimental site. The site is situated in a semi-arid zone, where the mean annual rainfall is typically less than 500 mm. The majority of precipitation (approximately 70-80%) occurs during the monsoon season, from July to September. The characteristics of various meteorological parameters for each week during the study period are presented in Figure 1. In terms of temperature, the mean values of minimum (T_{min}) and maximum (T_{max}) temperatures were higher

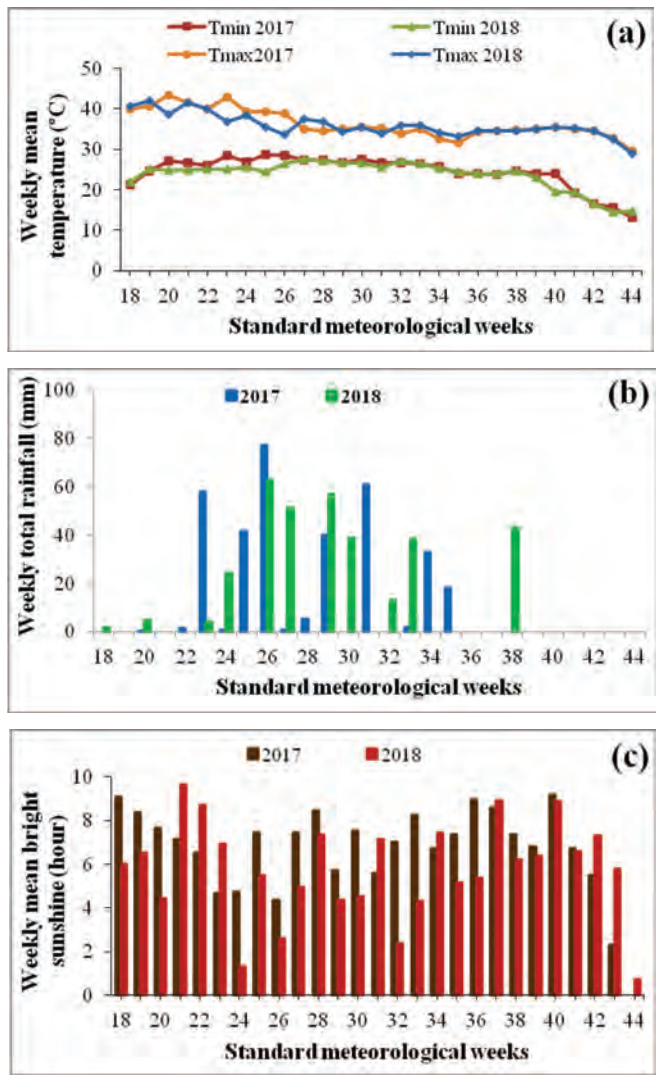


Fig. 1. Climatic characteristics of the study period (2017 and 2018) (a) Weekly mean minimum and maximum temperatures, (b) Weekly total rainfall and (c) Weekly mean bright sunshine hours

in the study year of 2017 (23.7°C and 35.9°C, respectively) compared to 2018 (22.9°C and 35.5°C). More specifically, the T_{min} ranged from 14.5-27.7°C in 2017 and from 15.2-26.6°C in 2018, while the T_{max} ranged from 28.9-42.0°C in 2017 and from 28.7-43.3°C in 2018. Additionally, weekly sunshine hours during the study period varied between 2.3-9.1 hours/day in 2017 and 0.7-9.6 hours/day in 2018. Total rainfall during the crop growing period was nearly identical in both years, with 338.2 mm in 2017 and 339.4 mm in 2018.

CROPGRO-cotton model

The CROPGRO-Cotton model, which is one of the crop modules within the Cropping System Model (CSM) framework of DSSAT v4.7, was utilized to compare model outputs with ground truth data from the field experiment. This model simulates daily phenological development and growth in response to environmental factors, including soil conditions, weather patterns, and management practices. The processes modelled by CROPGRO-Cotton encompass various aspects of crop growth and development, such as the duration of different growth stages, the development of both vegetative and reproductive plant parts, leaf and stem extension growth, leaf senescence, and biomass production. Additionally, the model accounts for the partitioning of biomass among different plant parts and dynamics of the root system. The model also includes subroutines for simulating soil-crop interactions, including soil water balance and nitrogen (N) balance. It is capable of modelling the effects of nitrogen deficiency and soil water deficit on crop growth.

Genetic coefficients

The genetic coefficients that describe the phenology and seed cotton yield components of a specific cotton variety or hybrid are scalar values, which are subsequently converted to physiological parameters within the model. To evaluate the model's performance in relation to seed cotton yield, as influenced by different Bt cotton hybrids and varying nitrogen (N) scheduling, the genetic coefficients used in this study were derived and calibrated by Dhir *et al.* (2021) for the Bt cotton hybrid RCH-773 BGII, and by Kaur (2018) for the Bt cotton hybrids NCS-855 BGII and RCH-650 BGII. These coefficients were specifically calibrated for the South-Western region of Punjab using the GENCALC software (DSSAT v4.6).

Statistical analysis

Seed cotton yield was analyzed using standard deviation (SD), which measures the amount of variability within a dataset. A lower SD indicates that the values are closer to the mean, reflecting less variability. Additionally, root mean square error (RMSE) was used to assess how closely the data points align with the best-fit axis, providing a measure of the model's prediction accuracy. The model's performance was further evaluated using d-statistics and R^2. These metrics facilitated a comparative evaluation of model performance across different locations, while linear regression analysis helped assess model stability under varying climatic conditions. A comparative and statistical analysis was conducted for actual versus simulated seed cotton yield data, considering treatments, years, and the overall model output (which combined all treatments and years).

RESULTS AND DISCUSSION

Effect of nitrogen scheduling on growth and yield attributes

Plant height is a critical characteristic of any cotton variety or hybrid, and significant variations were observed across nitrogen (N) scheduling treatments. A noticeable increase in plant height during both years of the study highlights the importance of applying nitrogen during the initial stages of crop growth, particularly at the time of the first irrigation. The application of 50% of the total nitrogen at the first irrigation significantly enhanced plant height during the early growth stages. In contrast, the treatment with only two nitrogen splits (N_1) resulted in shorter plants. This difference can be attributed to the improved vegetative growth from the adequate nitrogen application during the early stages, which also influenced the number of sympods per plant. The number of sympods was 20.6% and 5.3% higher in N_3 than in N_1 and N_2, respectively. During the fruiting period, similar trends were observed. The number of bolls was significantly higher in the N_2 and N_3 treatments compared to N_1, with a reduction of 12.2% and 6.6% in boll numbers per plant in N_1 relative to N_3 and N_2, respectively. Boll weight followed the same pattern as boll number, with higher weights recorded in N_2 and N_3 treatments. Seed cotton yield was highest in N_3, followed by N_2, and lowest in N_1, across both years. These results align with findings by Lemon *et al.* (2009), who reported that cotton requires minimal nitrogen during the early growth stages. In the present study, where nitrogen was not applied at sowing but half was applied at the first irrigation and the remaining nitrogen was split between the start of flowering and 50% flowering, the highest seed cotton yield was achieved. This confirms the importance of nitrogen application at critical growth stages. Pundarikakshudu and Raju (1995), as well as Lemon *et al.* (2009), recommended splitting nitrogen application to improve nitrogen use efficiency. By meeting the crop's nitrogen requirements at peak growth phases, such as flowering and boll development, the plant can maximize its yield potential. Specifically, Lemon *et al.* (2009) emphasized that nitrogen should be applied in three splits: one at 15-20 days after sowing (DAS), another at 45 DAS, and the final split at 60-90 DAS. They also highlighted that the second split at 45 DAS is the most critical for maximizing yield. Moreover, it was recommended that nitrogen application be completed before the peak bloom period to ensure the crop's nitrogen needs during boll development are met. It was also advocated for split nitrogen applications, suggesting that a portion be applied pre-plant and the remainder before the first bloom to optimize nitrogen use efficiency and improve yields (Anonymous, 2007).

Lori and Tyson (2019) highlighted that late nitrogen (N) applications can help mitigate the negative effects of nitrogen deficiency on cotton yields. Specifically, when nitrogen is applied in splits, with half or less of the total nitrogen applied during pre-planting or at planting, side dressing the remainder of the nitrogen no later than the early square stage can enhance cotton yields. Additionally, in nitrogen-deficient cotton, late nitrogen applications can alleviate some of the yield reduction caused by insufficient nitrogen supply. In contrast to these findings, Zhao *et al*. (2010) reported that cotton's maximum nitrogen uptake occurs between 54 and 110 days after planting. Similarly, Wang *et al*. (2003) found that peak nitrogen absorption typically occurs around 90 days after planting. This suggests that nitrogen application during the flowering and boll development stages may be particularly beneficial. Tang *et al.* (2012) also emphasized that late nitrogen applications are more effective in increasing nitrogen use efficiency (NUE) and promoting nitrogen accumulation during the fruit development stage in cotton. It is generally not recommended to apply all nitrogen as a basal dose in cotton, as nearly 80% of applied nitrogen is lost under field conditions when applied in this manner, compared to only about 40% loss with topdressing (Yang *et al*., 2013). Moreover, Yang *et al.* (2013) found that maximum nitrogen accumulation occurs during the reproductive stage, particularly in seeds, which are a major nitrogen reservoir in the plant. Similarly, Che *et al.* (2021) reported that the highest nitrogen uptake and accumulation occurred when nitrogen was applied at the flower-boll stage under irrigated conditions. In line with these observations, Trambadiya *et al.* (2022) found that higher seed cotton yields were obtained under spot application of nitrogen in four equal splits i.e. at basal, squaring, flowering, and boll development stages along with three foliar applications of 1% urea at squaring, flowering, and boll formation stages.

Effect of cultivars on growth and yield attributes

The data presented in Table 2 reveal significant variations among the cotton hybrids in terms of key

Table 2. Response of various *Bt* cotton hybrids and split application of nitrogen on yield attributes and seed cotton yield

Treatment	Plant height (cm)			Sympods (no.)			Bolls/plant (no.)			Boll weight (g)			Seed cotton yield (kg/ha)		
	2017	2018	Mean	2017	2018	Mean	2017	2018	Mean	2017	2018	Mean	2017	2018	Mean
V_1	145.1	147.8	146.5	22.9	23.3	23.1	42.8	43.6	43.2	3.67	3.74	3.70	2614	2733	2674
V_2	155.1	156.9	156	27.3	28.8	28.1	47.3	49.5	48.4	3.89	3.92	3.90	2944	3092	3018
V_3	146.1	148.9	147.5	25.7	25.6	25.8	43.4	44.9	44.1	3.73	3.75	3.74	2808	2893	2850
CD ($p\leq0.05$)	6.13	NS	3.57	2.90	2.89	1.53	NS	4.48	2.56	NS	NS	NS	236	261	128
N_1	144.5	146.9	145.7	22.2	22.4	22.3	41.2	43.3	42.3	3.53	3.61	3.57	2653	2755	2704
N_2	150.2	151.8	151.0	26.2	27.0	26.6	44.9	45.7	45.3	3.73	3.75	3.74	2723	2879	2801
N_3	151.5	154.9	153.2	27.5	28.7	28.1	47.4	49.1	48.2	4.03	4.04	4.03	2991	3084	3037
CD ($p\leq0.05$)	5.15	4.49	2.93	3.55	3.54	1.86	4.04	3.42	2.30	023	0.30	0.16	205	245	138

V_1: RCH 650
V_2: RCH 773
V_3: NCS 855
N_1: ½ N at 1st irrigation +½ N at 50% flowering
N_2: ¼ N at 1st Irrigation + ¼ N at 2nd irrigation + ½ N at 50 % flowering
N_3: ½ N at 1st Irrigation + ¼ N at start of flowering + ¼ N at 50% flowering

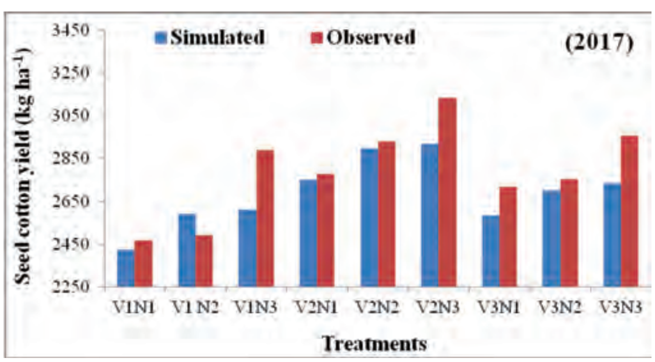
growth attributes, including plant height, number of sympods per plant, and yield components such as bolls per plant, boll weight, and seed cotton yield. During the first year of the study (2017), a significant increase in plant height was observed in the cultivar RCH 773 (155.1 cm) compared to RCH 650 (145.1 cm) and NCS 855 (146.1 cm). However, in the second year (2018), there were no significant differences in plant height among the hybrids. The pooled mean of both years showed that RCH 773 (V_2) had the tallest plants, while RCH 650 (V_1) had the shortest. Regarding the number of sympods per plant, RCH 773 recorded the highest values in both years, being 17.8% and 8.2% superior to RCH 650 (V_1) and NCS 855 (V_3), respectively. The number of bolls per plant showed no significant differences during the first year (2017). However, in the second year (2018) and in the pooled data, RCH 773 (V_2) had a significantly higher number of bolls per plant compared to both RCH 650 and NCS 855, although the latter two hybrids were statistically similar to each other. Boll weight remained largely consistent across the hybrids and did not show significant variation. In terms of seed cotton yield, RCH 773 achieved the highest yield, followed by NCS 855. The seed cotton yield was 12.9% and 5.9% lower in RCH 650 and NCS 855, respectively, compared to RCH 773. The superior performance of RCH 773 in terms of seed cotton yield can likely be attributed to its genetic characteristics and its responsiveness to nitrogen scheduling on light-textured soils. These factors contributed to higher yields in RCH 773 compared to the other hybrids.

CROPGRO-cotton model in terms of seed cotton yield

Evaluation of the CROPGRO–Cotton model in terms of seed cotton yield based on sowing dates and varying nitrogen levels using experimental data of *kharif* 2017 and 2018 are illustrated in Fig. 2, while statistics for the evaluation of the model is given in Table 3.

Among the various treatments, including different Bt cotton hybrids and nitrogen levels, the observed seed cotton yield ranged from 2467 to 3131 kg ha^{-1} in 2017 and from 2603 to 3340 kg ha^{-1} in 2018. In comparison, the simulated seed cotton yield ranged from 2423 to 2917 kg ha^{-1} in 2017 and from 2738 to 3230 kg ha^{-1} in 2018 (Fig. 2). Among the Bt cotton hybrids, the highest observed and simulated seed cotton yields were recorded for RCH 773 BGII (3018 and 3029 kg ha^{-1}, respectively), followed by NCS 855 BGII (2850 and 2794 kg ha^{-1}), while the lowest yields were observed for RCH 650 BGII (2674 and 2664 kg ha^{-1}). In terms of nitrogen application, the highest observed and simulated seed cotton yields were found under the N_3 treatment (3038 and 2875 kg ha^{-1}, respectively), followed by N_2 (2801 and 2851 kg ha^{-1}). The lowest yields were recorded under the N_1 treatment (2704 and 2761 kg ha^{-1}). Notably, the model generally tended to underestimate the simulated seed cotton yield compared to the observed values. However, both observed and simulated seed cotton yields showed an increase with a greater number of nitrogen splits. These findings align with previous studies by Prakash and Prasad (2000) and Kumbhar *et al.* (2008), which also highlighted the role of nitrogen in enhancing seed cotton yield.

The statistical analysis of the model's performance for seed cotton yield simulation showed a strong correlation between the simulated and observed yields. For the overall dataset, the model demonstrated a good fit, with R^2 = 0.60, d-statistic = 0.87, and RMSE = 145.53, indicating reasonable accuracy in simulating seed cotton yields. When comparing the two crop seasons, the simulated seed cotton yield showed a lesser deviation from observed values in the 2018 crop season, with a lower RMSE of 139.85 and a higher d-statistic of 0.86.



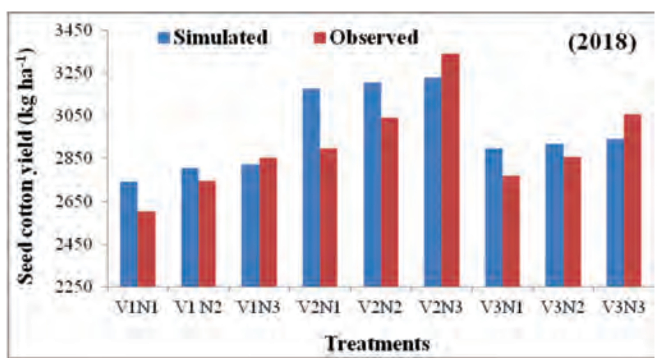


Fig. 2. Observed vs. simulated seed cotton yield (kg ha^{-1}) under different nitrogen application timings for three Bt cotton hybrids at Bathinda, 2017 and 2018

Note: Hybrids-RCH 650 BGII (V_1), RCH 773 BGII (V_2), NCS 855 BGII (V_3); Nitrogen timings: Two-split (N_1)-1/2 N at 1st irrigation+1/2 N Flowering, Three-split (N_2)-1/4 N at 1st Irrigation + 1/4 N at 2nd irrigation +1/2 N at flowering, Three-split with delayed flowering application (N_3)-1/2 N at 1st Irrigation + 1/4 N at start of flowering +1/4 N at 50% flowering

Table 3. Statistics for the evaluation seed cotton yield model performance across different hybrids and nitrogen levels at Bathinda, 2017 and 2018

	Mean			Standard Deviation		r-Square	Mean Difference	Mean Absolute Difference	RMSE	d-Stat	Total Number of Observations
	Observed	Simulated	Ratio	Observed	Simulated						
Overall	2847	2829	1.00	211.95	214.78	0.60	-18	122	145.53	0.87	18
2017	2789	2689	0.97	203.77	148.63	0.70	-100	122	151.00	0.83	9
2018	2906	2969	1.02	203.66	176.15	0.63	63	122	139.85	0.86	9
V_1	2674	2664	1.00	165.07	138.48	0.38	-10	108	135.51	0.79	6
V_2	3018	3029	1.00	182.32	183.17	0.35	11	138	166.12	0.78	6
V_3	2850	2794	1.00	122.16	131.35	0.31	-56	120	132.60	0.73	6
N_1	2704	2761	1.02	136.55	237.43	0.74	57	125	150.12	0.84	6
N_2	2801	2851	1.00	172.66	193.27	0.86	50	78	88.97	0.94	6
N_3	3038	2875	0.90	165.40	193.42	0.83	-163	163	181.90	0.79	6

V_1: RCH 650
V_2: RCH 773
V_3: NCS 855
N_1: ½ N at 1st irrigation +½ N at 50 % flowering
N_2: ¼ N at 1st Irrigation + ¼ N at 2nd irrigation + ½ N at 50 % flowering
N_3: ½ N at 1st Irrigation + ¼ N at start of flowering + ¼ N at 50% flowering

Table 4. Effect of *Bt* cotton hybrids and split nitrogen application on soil chemical properties at the end of the experiment

Treatment	pH		EC (dSm^{-1})		N (kg/ha)		P (kg/ha)		K (kg/ha)	
	0-15	**15-30**	**0-15**	**15-30**	**0-15**	**15-30**	**0-15**	**15-30**	**0-15**	**15-30**
V_1	8.23	8.27	0.332	0.335	65.5	46.0	14.9	12.7	333.2	204.7
V_2	8.25	8.18	0.328	0.327	61.8	46.8	14.1	12.3	328.9	200.8
V_3	8.23	8.15	0.319	0.316	57.9	43.7	14.4	12.0	326.9	203.7
CD ($p \le 0.05$) A	**NS**	**0.079**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
N_1	8.25	8.10	0.332	0.329	67.2	50.3	14.6	12.7	333.0	202.0
N_2	8.24	8.23	0.326	0.325	61.1	46.6	14.4	12.5	330.7	205.6
N_3	8.25	8.25	0.321	0.323	57.0	39.5	14.1	11.9	325.3	201.6
CD ($p \le 0.05$) B	**NS**	**NS**	**NS**	**NS**	**6.55**	**6.0**	**NS**	**NS**	**5.37**	**3.06**

V_1: RCH 650
V_2: RCH 773
V_3: NCS 855
N_1: ½ N at 1st irrigation +½ N at 50 % flowering
N_2: ¼ N at 1st Irrigation + ¼ N at 2nd irrigation + ½ N at 50 % flowering
N_3: ½ N at 1st Irrigation + ¼ N at start of flowering + ¼ N at 50% flowering

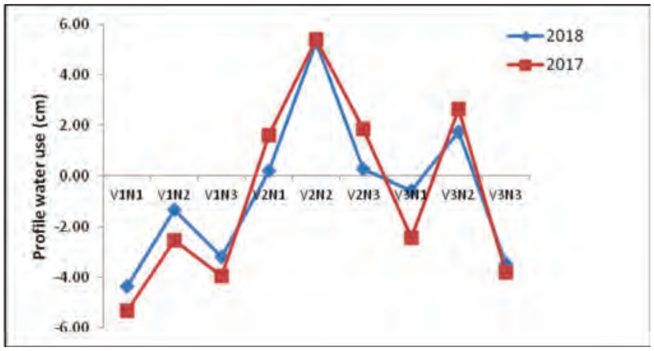


Fig. 3. Profile water use (cm) under various treatments in 2017 and 2018

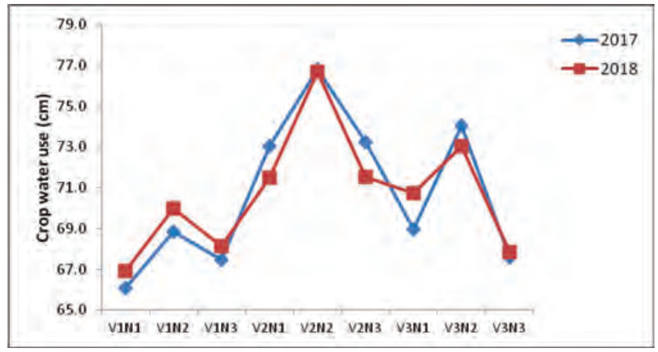


Fig. 4. Total crop water use (cm) under various treatments in 2017 and 2018

In contrast, the 2017 crop season had a higher RMSE (151.0) and a lower d-statistic (0.80), indicating slightly higher deviations in that year. Regarding the nitrogen application levels, the simulation was closest to the observed yields under the N_2 treatment, with $R^2 = 0.86$, d-statistic = 0.94, and RMSE = 88.97, reflecting minimal error. On the other hand, the simulated yield under N_3 had a higher RMSE (181.90) and a lower d-statistic (0.79), indicating greater deviations from the observed values, while N_1 showed intermediate results (R^2 = 0.83, d-statistic = 0.84, RMSE = 150.12). Among the Bt cotton hybrids, the model's predictions were closest to the observed seed cotton yield for RCH 773 BGII, with an RMSE of 132.60, indicating smaller discrepancies between simulated and observed values. In contrast, the model showed a higher RMSE for NCS 855 BGII (166.12) and RCH 650 BGII (135.51). However, RCH 650 BGII had the highest R^2 value (0.38) and d-statistic (0.79), indicating a stronger overall fit between the simulated and observed yields compared to RCH 773 BGII (R^2 = 0.35, d-statistic = 0.78) and NCS 855 BGII (R^2 = 0.31, d-statistic = 0.73).

Effect of cultivars and nitrogen scheduling on soil properties

At the conclusion of the experiment, various soil parameters were assessed. The soil pH did not show significant differences across the upper soil layer (0-15 cm) among the treatments, although the highest pH was recorded under the RCH 650 BGII variety. Similarly, the electrical conductivity (EC) did not exhibit significant variations across the different varieties or nitrogen scheduling treatments. The nitrogen (N) content in the soil was similar across the varieties but showed significant variation with different nitrogen scheduling treatments. The highest nitrogen content was observed under the N_1 treatment, while the lowest was recorded under N_3 in both soil profiles. In contrast, the phosphorus (P) content remained consistent across all treatments, showing no significant changes. The potassium (K) content followed a similar trend to nitrogen, with higher values observed under the N_3 treatment compared to N_1 and N_2. This suggests that nitrogen (N) and potassium (K) were more efficiently utilized under the N_3 treatment, likely due to the higher nitrogen uptake by plants in this treatment. Supporting these findings, Kaur and Pannu (2008) reported that split nitrogen applications, particularly when applied later in the crop's growth cycle, reduced nitrogen losses and enhanced nitrogen uptake, leading to increased yields and lower residual nitrogen in the soil. Similarly, Trambadiya *et al.* (2022) found that N, P, and

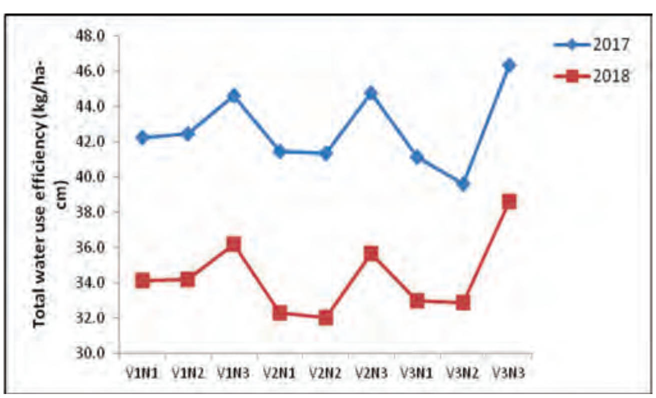


Fig. 5. Total water use efficiency (kg ha^{-1} cm^{-1}) under various treatments in 2017 and 2018

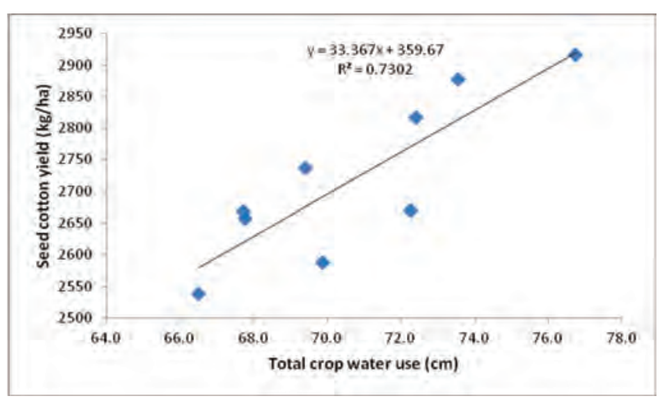


Fig. 6. Relationship between seed cotton yield and total crop water use under various treatments

K concentrations were higher under N spot application in four equal splits (at basal, squaring, flowering, and boll development stages), along with foliar application of 1% urea at squaring, flowering, and boll formation, compared to the control treatment.

Effect of cultivars and nitrogen scheduling on water use efficiency

The cotton crop received a total of five irrigations, each with a depth of 7.5 cm, amounting to 37.5 cm of irrigation water applied (IWA) during both years of the study. Additionally, the total rainfall was recorded as 33.9 cm in 2017 and 33.8 cm in 2018. The Profile Water Use (PWU) for the entire soil profile (0-180 cm) was measured post-harvest (Fig. 3). It was observed that profile water was added to the soil profile under the RCH 650 BGII variety in both years. On the other hand, maximum profile water use was recorded under the RCH 773 BGII variety, with values of 2.96 cm in 2017 and 1.94 cm in 2018. In terms of nitrogen scheduling, the N_3 treatment exhibited the highest profile water use in both years, while N_1 and N_2 treatments resulted in water being added to the profile (Fig. 3). When examining total crop water use (the mean across both years), the highest water usage was recorded under NCS 855 BGII hybrid (71.4 cm), followed closely by RCH 773 BGII hybrid. Regarding nitrogen schedules, the highest total crop water use was observed under the N_3 treatment (73.2 cm), followed by N_1 (69.5 cm) and N_2 (69.3 cm) treatments. This study found a strong positive relationship between seed cotton yield and total crop water use (r = 0.73), as illustrated in Fig. 6. In terms of Water Use Efficiency (WUE), the highest efficiency was observed in RCH 650 BGII (43.1 kg ha^{-1} cm^{-1}), followed by RCH 773 BGII (42.5 kg ha^{-1} cm^{-1}) and NCS 855 BGII (42.4 kg ha^{-1} cm^{-1}). Among nitrogen schedules, the N_3 treatment demonstrated the highest water use efficiency (45.3 kg ha^{-1} cm^{-1}).

CONCLUSION

The highest seed cotton yield and water use efficiency were observed when nitrogen was applied in three splits: half at the first irrigation, one-quarter at the start of flowering, and the final one-quarter at 50% flowering. This split application of nitrogen, extending through the later growth stages (flowering), ensured consistent availability of nitrogen throughout the crop's growth period, promoting optimal growth and yield. Among the different Bt cotton hybrids, RCH 773 outperformed the other hybrids in terms of seed cotton yield. The results from model calibration and validation demonstrated that the CROPGRO-Cotton model accurately simulated the growth and development of cotton, with the model's predictions aligning closely with the observed values. Statistical analysis further confirmed the accuracy of the model, as the simulated and observed seed cotton yields were in close agreement. Specifically, the N_3 nitrogen schedule resulted in lower RMSE and higher R^2 and d-Stat values compared to the other nitrogen schedules (N_1 and N_2), indicating better model performance when N was applied in three splits. Overall, the CROPGRO-Cotton simulation model proved to be a reliable tool for simulating seed cotton yield under varying nitrogen schedules and Bt cotton hybrids. The relatively small discrepancies between the simulated and observed yields suggest that the model can be effectively used as a decision-support tool for cotton production in the region. By utilizing the model, farmers could optimize nitrogen management strategies, leading to higher seed cotton yields and improved resource use efficiency.

Authors' contribution:

Conceptualization and designing of research work (AK, KSS, ST): Execution of field experiment and data collection (AK, KSS, ST): Analysis of data and interpretation (AK, RKP, KSS).

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