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Research paper

Optimization of irrigation (ET_c) and nitrogen levels under drip fertigation in okra (*Abelmoschus esculentus* L.) using response surface methodology (RSM)

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A comprehensive field investigation was conducted to enhance the productivity, profitability, and water use efficiency (WUE) of summer okra through the optimization of irrigation and nitrogen fertilizer application. The study involved 3 irrigation levels – 0.75 E_{pan} (pan evaporation) as I_1, 1.00 E_{pan} as I_2, and 1.25 E_{pan} as I_3 – as the main plot factors, and 4 nitrogen concentrations – 75% recommended nitrogen dose (RDN) as N_1, 100% RDN as N_2, 125% RDN as N_3, and 150% RDN as N_4 – as the subplot variables. The results of the study revealed a significant influence of irrigation and nitrogen levels on various key parameters. Above-ground dry matter, yield, plant height, WUE, net returns, and benefit-to-cost ratio (B:C) exhibited an incremental trend with increasing irrigation and nitrogen levels, up to a certain threshold. Beyond this threshold, further increments in irrigation and nitrogen led to diminishing returns. The models developed for estimating crop yield, above-ground dry matter, plant height, WUE, net returns, and B:C demonstrated impressive accuracy, with high coefficients of determination (R^2) and satisfactory precision. The optimized irrigation level (crop evapotranspiration, ET_c) ranged from 418.39–441.23 mm. At the same time, the ideal nitrogen application rate was found to be in the range of 167.04–176.13 kg N/ha. These optimal conditions resulted in peak crop yield of 28 295 kg/ha, above-ground dry matter of 6 709.1 kg/ha, plant height of 66.3 cm, WUE of 5.26 kg/m^3, B:C of 4.54, and net returns amounting to 441 133 INR/ha. In conclusion, the application of response surface methodology facilitated the identification of the impact of each factor on individual responses, as well as the determination of optimal conditions that simultaneously maximize multiple desirable outcomes. These findings hold significant promise for improving the cultivation of summer okra while optimizing resource use and economic returns.

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INTRODUCTION

Abelmoschus esculentus L., commonly known as okra or lady's finger, is primarily cultivated in tropical and subtropical regions across the globe. It serves as a commercially viable crop, under both rainfed and irrigated conditions, in many countries, including India, Turkey, Iran, Yugoslavia, Bangladesh, Afghanistan, Pakistan, Burma, Japan, Malaysia, Brazil, Ghana, Ethiopia, Cyprus, and the southern United States. In the Hindi language, the vegetable is referred to as *bhindi*, whereas in the Sanskrit language it is *asra-pattraka* (Kumar et al., 2023). In India, it is grown on 531 000 ha of land with a total yield of 6 371 000 t of produce annually, with a productivity of 12.2 t/ha (Government of India, 2020).

India accounts for 70% of global okra production (Farre and Faci, 2006). The crop is grown for its tender green fruits in a variety of climatic and soil environments, during the spring-summer and rainy seasons. It is a good source of protein, carbohydrates, lipids, and vitamins A, B, and C. Recently, okra has also been used for its health benefits, as it contains several important bioactive chemicals (Elkhalifa et al., 2021).

Summer okra is a prominent agricultural crop cultivated in the arid and semi-arid regions of Telangana State, covering a total area of 4 410 ha which includes 810 ha in summer (Kalavathy et al., 2009), producing 85 290 t and 19.24 t/ha. Micro-irrigation in Telangana has developed rapidly to cover 300 276 ha by 2018/19, due to the active role played by the Telangana Micro Irrigation Project (Telangana Irrigation Department, 2020). There is scope to increase this area as Telangana State has 828 796 ha supplied by borewells and 1 498 955 ha under major, medium and minor irrigation projects (Telangana Water Resources Information System, 2020).

A suitable water supply to maintain sufficient soil moisture throughout the growth period is essential for yield enhancement, especially in summer. The influence of water deficit on yield is greater in regions experiencing high temperatures and low humidity (Vadar et al.,2019). Okra is extremely sensitive to soil moisture levels. Since both water stress and excess water impede plant development and fruit production, controlled irrigation is essential for high yield (Al-Harbi et al., 2008). Hence, optimum irrigation plays an important role in crop yield, and accurate assessment of plant water status becomes crucial. Okra thrives in tropical and subtropical regions, but growth and productivity are subject to various environmental factors, including nutrient availability, especially nitrogen. Strategic application of irrigation and nitrogen at the appropriate time can significantly contribute to the enhanced development, yield, and quality of crops.

While previous research has explored the optimisation of water supply and fertiliser input to enhance okra production, water productivity, and net returns, limited attention has been given to the improvement of green pod yield, crop water productivity, and economic benefits through optimal water and fertiliser management. This study aimed to establish quantitative correlations between various factors, such as plant height, above-ground matter, green pod yield, water use efficiency (WUE), and net returns, in relation to water and fertiliser inputs. The objective was to develop an optimised water and fertiliser management strategy for summer okra cultivation in Telangana, India. The economic efficiency, WUE, and fertiliser use efficiency were assessed using multiple regression analysis and likelihood estimation. In the pursuit of optimisation, several statistical methods such as response surface methodology, central composite design (CCD), and Box-Behnken design (BBD) have been developed to achieve improved outcomes within reduced timeframes. Moreover, they serve as a comprehensive and versatile tool for constructing empirical models and analysing the effects of many components, as well as examining the interactions among variables and assessing their statistical significance (Chen et al., 2022). Keeping this in mind, given the opportunity and research gap discussed above, the investigation of optimization of irrigation levels, quantification of water requirements under drip system and N levels for fertigation of a summer okra crop was prioritized.

MATERIALS AND METHODS

Description of experimental plots

The field experiment was carried out in the summer of 2021 at the Water Technology Centre, College of Agriculture, Professor Jayashankar Telangana State Agricultural University, Rajendranagar, Hyderabad (17°19'24.7" N , 78°24'34.0" E at an altitude of 542.4 m amsl). The experimental site received 12.6 mm of precipitation overall during the summer growing season for okra. Soil texture is sandy clay soil which is low in nitrogen, high in phosphorus and potassium that is readily available, medium in organic carbon content, alkaline in reactivity, and non-saline. Irrigation water was neutral (7.20 pH) and classified as C3 class, suggesting that it is suitable for irrigation when following good management practices. (Table 1)

Experimental design

The okra variety Radhika was used. The drip irrigation lateral was the inline type with a dripper spacing of 40 cm and discharge rate of 2 L/h. The experiment was laid out in a split-plot design consisting of 12 treatments replicated thrice, i.e., drip irrigation scheduled at 0.75 (I_1: 366 mm ET_c), 1.0 (I_2: 441 mm ET_c) and 1.25 (I_3: 499 mm ET_c) E_{pan} and 4 nitrogen concentrations – 75% RDN (N_1), 100% RDN (N_2), 125% RDN (N_3), and 150% RDN (N_4). The recommended dose of fertilizers (RDF) was 150:75:75 kg NPK/ha. The entire dose of P_2O_5 and K_2O in the form of DAP and MOP was applied as basal, nitrogen was applied as fertigation in 18 splits in the form of urea with 4-day interval, from 15 days after sowing to final picking. However, in determining whether irrigation levels close to 1.0 E_{pan} (pan evaporation in mm/day) were ideal for okra cultivation, it was discovered that okra output increased with increasing irrigation levels up until 1.0 E_{pan} (I_2). One drip lateral was located in the middle of the crop row. Each dripper corresponded to two okra plants. The okra was irrigated every alternate day, with irrigation postponed to the next day in the case of rainfall. Total daily ET_c (crop evapotranspiration) throughout the irrigation scheduling was utilised to determine the amount of irrigation to be applied during each event. Water lost in irrigation pipelines was not included in the actual irrigation amount, and the coefficient of irrigation water utilisation was assumed to be 0.95, which correlates with the 95% field efficiency of the installed in-line drip system (Wu et al., 2014).

Water balance and crop evapotranspiration (ET_c)

Seasonal crop evapotranspiration (ET_c) was computed using the water balance equation (FAO, 1995) and soil water measured using the gravimetric sampling method. The total of seasonal water loss, rainfall, and irrigation over the same period was used to compute water consumption. The water balance equation is as follows:

$$ET_c = I + P - \Delta S - D \tag{1}$$

where: ET_c is crop evapotranspiration from the effective root zone depth (mm), I is irrigation (mm), P is precipitation (mm), ΔS is changes in soil water storage over time, Δt (days) for the period for which ET_c and K_c are computed (mm), and D is deep percolation losses below the root zone. Using E_{pan} data the crop evapotranspiration is derived using the following equation:

$$ET_c = ET_0 \times K_c \tag{2}$$

where: ET_o is reference evapotranspiration (mm) and K_c is the crop coefficient.

Crop biometric observations, green fruit yield and economics

The height of plants was measured using a sample of 5 randomly selected plants within each treatment group at the final stage of harvesting. Above-ground dry matter was determined by randomly uprooting plants from the row that was close to the net plot rows, but excluding the border rows. The subterranean section of the plant was disposed of. The aerial components of the plant samples were divided into leaves and stems, and subjected to desiccation through exposure to sunlight, followed by further air drying in an oven at a temperature of 65°C. The fresh pod yield was determined by quantifying the weight of the collected pods from the initial picking to the ultimate harvesting, and overall pod yield calculated (kg/ha). Water use efficiency (WUE) was determined by dividing the crop yield by the total amount of water applied. The economic analysis involved considering the actual expenses incurred for different activities, prevailing wages for workers, the current pricing of inputs, and the market value of the output. The net returns were computed based on prevailing agricultural market rates.

Table 1. Physical properties and moisture retention characteristics of the experimental soil

Depth	Sand (%)	Clay (%)	Gravel (%)	Silt (%)	BD (g/cc)	HC (mm/h)	WP (%)	FC (%)	SAT (%)	Soil type
0–20 cm	48.5	35.2	4.3	12	1.46	3.39	21.3	33	45	Sandy clay
20–30 cm	44	37	5	14	1.53	1.33	22.5	33.9	42.2	Clay loam
30–50 cm	42	38	5	15	1.54	0.91	23	34.5	41.8	Clay loam
>50 cm	52	33	6	9	1.61	1.61	20.1	30.2	39.1	Sandy clay loam

Note: BD – bulk density, HC – hydraulic conductivity, WP – wilting point, FC – field capacity, SAT – saturation

Response surface methodology (RSM)

The parameters used for the optimization of irrigation and nitrogen levels were analysed by response surface methodology (RSM) using central composite design (CCD). Because of the wide range of treatment combinations (combination of different levels of irrigation and nitrogen) using multi-factor experiments, selecting the best combination treatment is costly, complex, time-consuming and associated with experimental errors. RSM is suitable for fitting a quadratic surface and helps to optimize the process parameters using the minimum number of experiments, as well as to analyse the interaction between the parameters.

The first step in the design of the experimental procedure was to identify the input variables and the output (response) that will be measured. The statistical software used in the study was Minitab 18. There were then three main steps: choosing the experiments; planning and carrying out the best statistically designed experiments; creating a mathematical model by estimating the coefficients.

Analysis and prediction of the response while determining model adequacy helps to establish a strong correlation between the different polynomial expressions (Chen et al., 2022). A second-order polynomial expression was used in the RSM to construct a correlation between the k variables. Equation 3 can be used to illustrate the actual relationship between the independent control variables or factors, X_1, X_2, ... and X_k, and the response Y (dependent variable): Productivity, profitability and WUE were considered dependent variables for optimizing the combination and irrigation and nitrogen levels in this study, while irrigation (crop ET_c) and nitrogen levels were independent variables.

$$Y = f(X_1, X_2, \ldots, \ldots, \ldots, X_k) \tag{3}$$

Y = output (yield); inputs are X_1 as crop evapotranspiration (ET_c in mm) and X_2 as nitrogen levels.

For CCD and Box-Behnken design, second-order models are widely used: Equation 4 represents the quadratic model, which is close to optimization.

$$\begin{aligned} Y &= b_0 + b_1X_1 + \ldots + b_kX_k + b_{12}X_1X_2 + b_{13}X_1X_3 + \\ &\ldots + b_{k-1}, k\ X_{k-1}X_k + b_{11}X_1^2 + \ldots + b_{kk}X_k^2 + \varepsilon \end{aligned} \tag{4}$$

where: Y is dependent variables, outcome variables, or estimated responses in Eq. 4; independent variables are X_1, with the overall mean response b_0; b_1 is coefficients from a regression model; k is the number of independent variables; and ε is the error.

Description of the mathematical model applied to the observed values of the dependent variable Y is based on:

- Main effects for factor $X_1, \ldots, X_k$
- Their interactions (X_1X_2, X_1X_3, …, X_{k-1}, X_k)
- Their quadratic components (X_1^2, …, X_k^2).

There are no presumptions made about the amounts of the components, and any set of continuous values can be used to analyse the factors. The independent variables (I and N) including the coded and the actual levels are presented in Table 2.

Analysis of results

The results were statistically analysed using 2-factor split-plot design in the OP stat software (Sheoran, 2010) to test their significance at 5%. The critical difference (CD) at 5% level of probability was computed to check the significance of results.

RESULTS AND DISCUSSION

Water balance and crop evapotranspiration (mm)

During the summer, the average soil moisture content at 0–40 cm depth was significantly affected by drip irrigation levels (Fig. 1). An accumulative irrigation amount of 482.5 mm, 610 mm, 735.5 mm was applied at 0.75 E_{pan} (I_1), 1.00 E_{pan} (I_2), 1.25 E_{pan} (I_3), respectively. The soil moisture content data across the irrigation schedule shows that the soil layer at 20–30 cm holds more water than the top and bottom layers. The crop irrigated at 1.25 E_{pan} (I_3) recorded the highest moisture content across the soil layers. Moisture content decreased with the decreasing water supply scheduled at 1.0 E_{pan} (I_2) and 0.75 E_{pan} (I_1) treatments. The crop ET at various crop growth periods, i.e., from the initial stage (0–18 days) to the vegetative state (19–40 days), increased linearly and then decreased towards the senescence stage across the irrigation levels. Among the irrigation scheduling treatments, the crop irrigated at 1.25 E_{pan} (I_3) recorded maximum ET_c; which decreased with decreasing irrigation levels. Crop ET continues at potential rates, as shown by drip irrigation set at 1.0 E_{pan} and 1.25 E_{pan} treatments (Fig. 2), as long as the water availability meets the rate of water loss through transpiration by the crop canopy and evaporation from the surface (Dingre and Gorantiwar, 2020). But when the crop pulls water from the soil, the moisture content and water potential of the soil decrease, leading to poor soil water conductivity, which makes it harder for water to move through the soil. This tends to reduce the amount of water that gets to the plants, which significantly reduces crop ET as seen in deficit irrigation levels, i.e., in drip irrigation at 0.75 E_{pan} treatment.

Table 2. Coded and actual levels of independent variables for RSM

Run	Irrigation (I) (mm)	Nitrogen levels (N) (kg N/ha)	Coded values of I (X_1)	Coded values of N (X_2)
1	366	112.5	–1	0
2	366	150.0	–1	1
3	366	187.5	–1	2
4	366	225.0	–1	3
5	409	112.5	0	0
6	409	150.0	0	1
7	409	187.5	0	2
8	409	225.0	0	3
9	499	112.5	+1	0
10	499	150.0	+1	1
11	499	187.5	+1	2
12	499	225.0	+1	3

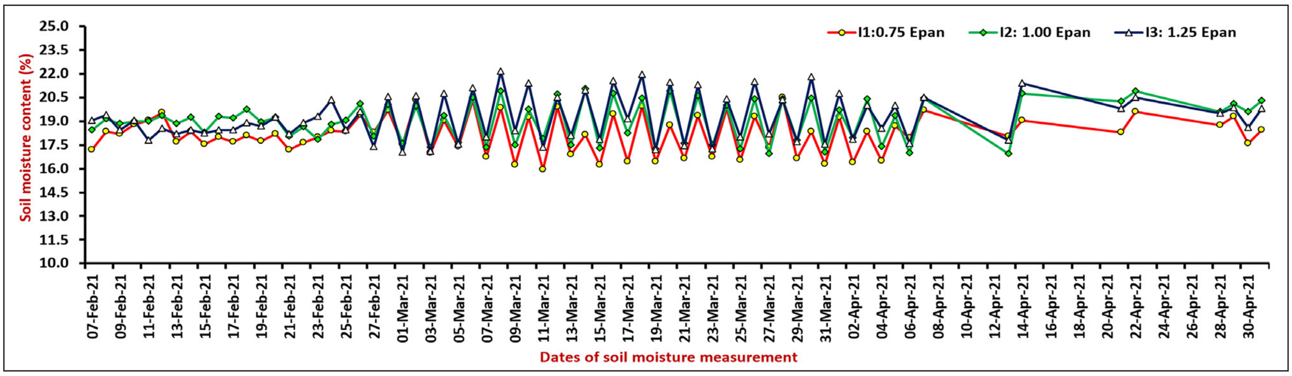

Figure 1. Mean soil moisture content under different drip irrigation scheduling for summer okra

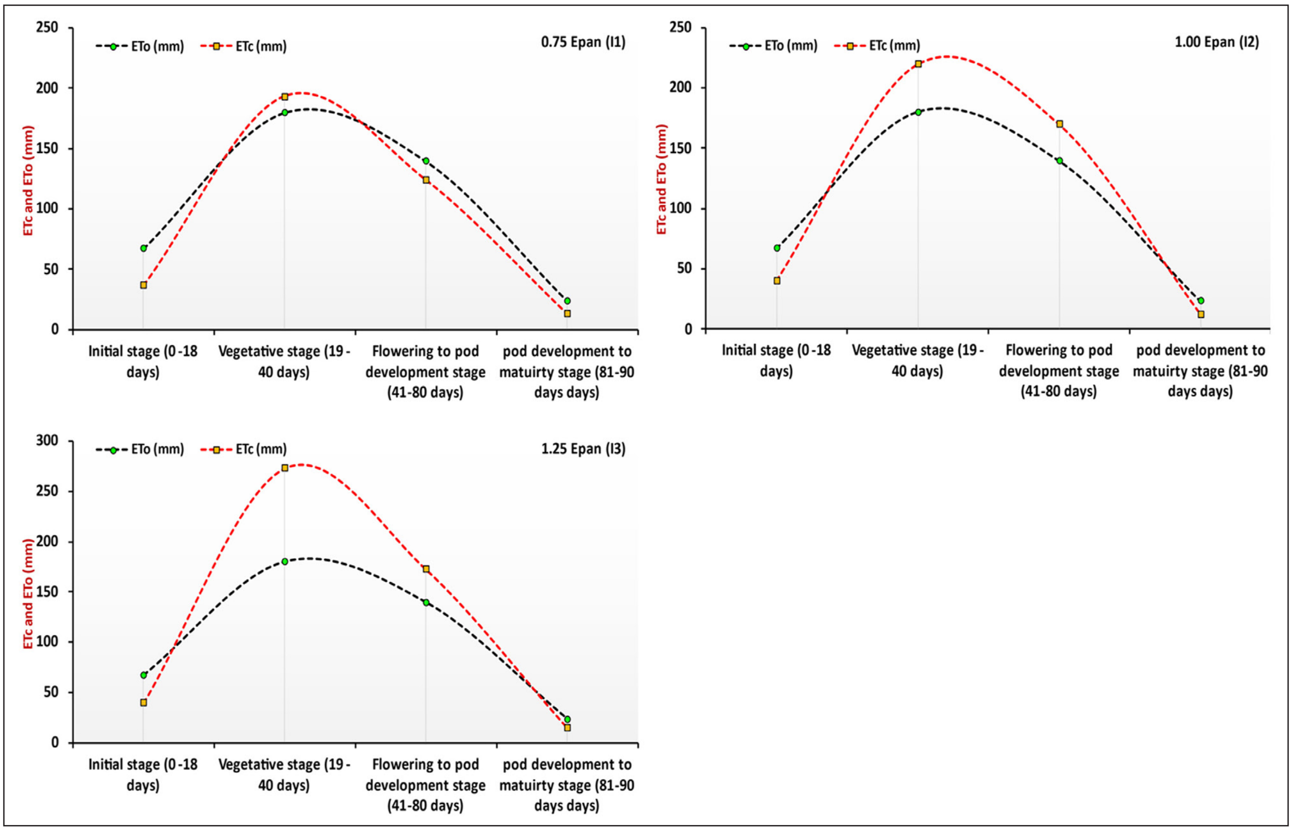

Figure 2. Reference evapotranspiration (ET_o) and crop evapotranspiration (ET_c) measured under different drip irrigation scheduling for summer okra

Yield, biometric observations and WUE

Figure 3 and Table 3 show the effect of irrigation and nitrogen levels on the yield, biometric observations and WUE of okra. The maximum yield, biometric observations and WUE were recorded with 100% RDN (N_2) treatment at 1.00 E_{pan} (I_2). The yield, biometric observations and WUE were reduced by increasing fertilizer amount above 100% RDN, indicating that excessive fertilizer application hinders the increase in plant height and accumulation of above-ground dry matter.

The maximum yield, biometric observations and WUE with I_2 (1.0 E_{pan}) irrigation scheduling were due to optimal moisture conditions prevailing in the rootzone throughout the crop growth period. Increasing the amount of irrigation above optimal likely hampered the availability of sufficient oxygen to the root zone and thus root respiration, resulting in a reduction in yield, biometric observations and WUE. The reduction in plant height at I_1 (0.75 E_{pan}) scheduling was due to deficit soil moisture conditions prevailing in the root zone throughout the crop growth period. These results are in line with the findings of Shivaraj et al. (2018), who reported that significantly taller plants were observed with drip irrigation scheduled at 80% ET and reduced plant height was recorded with 100% ET and 60% ET treatments.

Yield, biometric observations and WUE of okra increased with an increase in the nitrogen dose from 75% RDN (N_1) to 100% RDN (N_2), but a further increase in nitrogen dose reduced the above-ground dry matter content which influenced the yield and plant height of okra. Okra was shown to be inhibited by the rooting medium's excessive nitrogen levels – the organism's general tolerance to low nitrogen may be what causes the growth decline under high nitrogen availability. The plants did not display signs of toxicity brought on by too much nitrogen or signs of a nitrogen shortage (Brar and Singh, 2016). These results align with the findings of Uddin et al. (2014), who reported that the maximum above-ground dry matter was recorded with the application of 120 kg N/ha, which was on par with that achieved with 130 kg N/ha and significantly more than that with 110 kg N/ha and 0 kg N/ha.

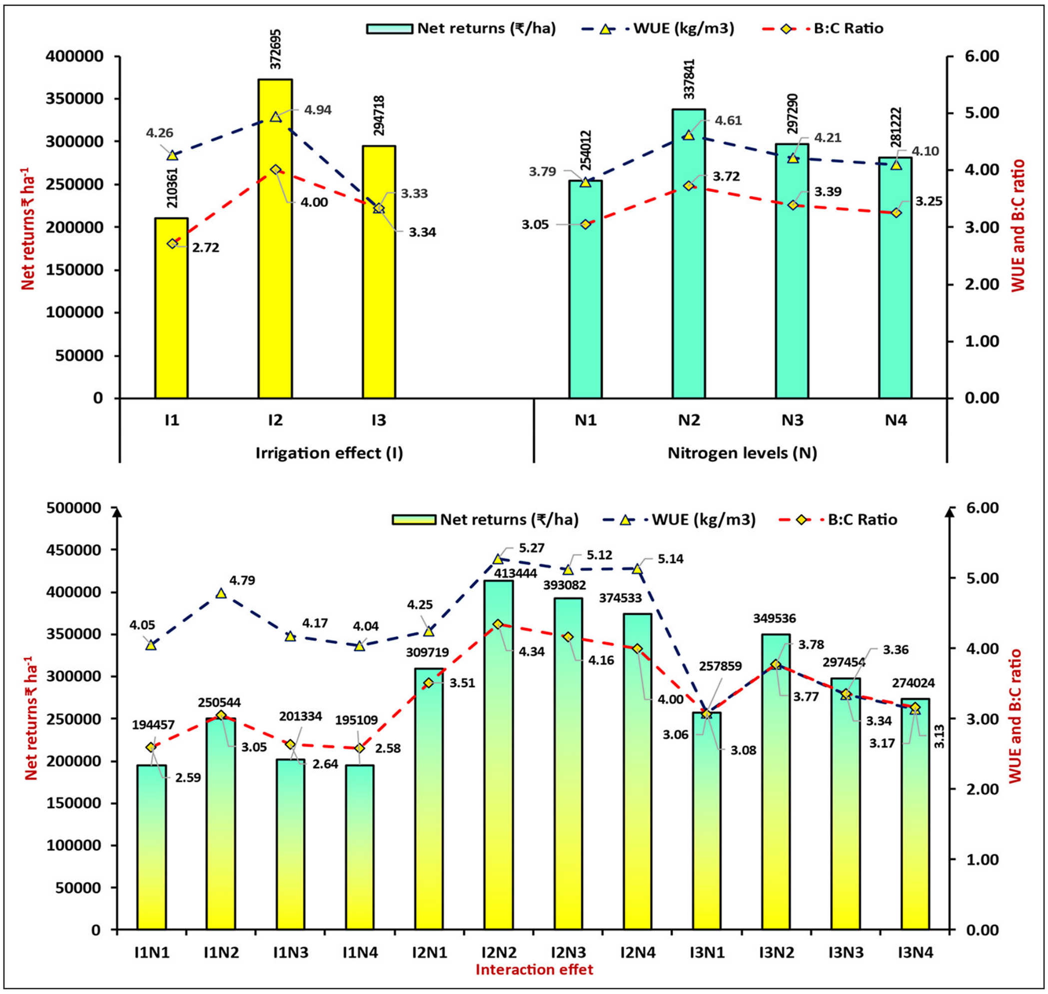

Figure 3. Effect of drip irrigation scheduling and nitrogen levels on economic returns and water use efficiency of summer okra

Table 3. Effect of drip irrigation scheduling and nitrogen levels on plant height (cm), above-ground dry matter (kg/ha) and yield (kg/ha) attributes of okra

Treatments	Plant height (cm)	Above-ground dry matter (kg/ha)	Yield (kg/ha)
		Irrigation effect (*I*)	
I_1	51.6	4 210	16 631
I_2	62.3	6 082	24 829
I_3	56.1	5 166	21 013
LSD ($p = 0.05$)	1.6	180	871
		Nitrogen effect (*N*)	
N_1	54.1	4 931	18 867
N_2	59.1	5 570	23 077
N_3	57.1	5 060	21 069
N_4	56.4	5 050	20 285
LSD ($p = 0.05$)	0.4	107	469
		Interaction (*I* x *N*)	
I_1N_1	49.2	4 094	15 810
I_1N_2	54.4	4 471	18 629
I_1N_3	52.0	4 104	16 188
I_1N_4	50.8	4 172	15 897
I_2N_1	60.3	5 757	21 651
I_2N_2	64.5	6 727	26 857
I_2N_3	62.8	5 944	25 859
I_2N_4	61.6	5 901	24 951
I_3N_1	53.0	4 941	19 141
I_3N_2	58.4	5 512	23 745
I_3N_3	56.5	5 132	21 160
I_3N_4	56.7	5 077	20 008
LSD ($p = 0.05$)	1.7	238	1 107

The interaction effects of irrigation and nitrogen levels on the yield of okra are shown in Table 3. Using irrigation scheduling at I_1 (0.75 E_{pan}) with increasing nitrogen from 75% to 100% RDN, the green pod yield was increased significantly from 15 810 to 18 629 kg/ha. Further increasing nitrogen dose from 100% to 125% RDN and from 125% to 150% RDN, the green pod yield was decreased significantly from 16 188 to 15 897 kg/ha, respectively. A similar trend was also reflected at 1.0 E_{pan} (I_2). At I_3 irrigation scheduling a significantly higher green pod yield (23 745 kg/ha) was recorded with 100% RDN compared to the other treatments, which was followed by 125% RDN (21 160 kg/ha). The lowest green pod yield was recorded with N_1 which was comparable with N_4 and significantly inferior to the green pod yield with N_2 and N_3 levels. Among the combination of treatments, the crop irrigation scheduled at I_2 (1.0 E_{pan}) in conjunction with 100% RDN (I_2N_2) recorded a maximum green pod yield of 26 857 kg/ha. However, this was comparable with 1.0 E_{pan} (I_2) in conjunction with 125% RDN (I_2N_3), giving a green pod yield of 25 859 kg/ha which was significantly higher than that for the rest of the treatment combinations.

The interaction effects of irrigation scheduling and nitrogen levels indicated that, for okra crops, 100% RDN is optimum for maximum green pod yield, irrespective of irrigation scheduling. Krittika and Misal (2018) found that maximum green pod yield was recorded with the application of 0.8 E_{pan} in conjunction with 80% RDN, followed by 1.0 E_{pan} in conjunction with 80% RDN. According to Bhatti et al. (2011) nitrogen is transported to the shoots under conditions of excessive nitrogen supply, where it is reduced. Nitrate reduction and assimilation need a lot of energy; for example, it takes 15 mol of ATP to reduce 1 mol of NO_3. Possible causes of the slower growth under excessive nitrogen include energy diversion. As evidenced by earlier studies (Payero et al., 2006; Pampolino et al., 2012; Djaman et al., 2013; Xu et al., 2014; Kresović et al., 2016) and the findings of the current research, there is a quadratic relationship between okra yield during the summer season and the levels of irrigation and nitrogen applied. The findings of this study indicate that the greatest crop yields were attained for the I_2N_2 treatment, which consisted of 1.00 E_{pan} combined with 150 kg N/ha. The significant increase in crop productivity can be attributed to the precise use of irrigation and fertilisation quantities (Wang et al., 2011; Chilundo et al., 2017).

The semi-arid regions of Rajendranagar in Telangana State, India, exhibit notable attributes such as ample sunlight and heat available for crop growth. These favourable conditions contribute to the accumulation of photosynthetic products, thus leading to an augmentation in green pod yield. However, an overabundance of water and nitrogen can cause plants to develop rapidly, leading to an excessive leaf area index. This can have an impact on the utilisation of light energy by crops and the efficient distribution of photosynthetic products. Hence, the use of appropriate irrigation and nitrogen management practises can effectively optimise the utilisation of light energy, thereby enhancing their photosynthetic efficiency. The impact of irrigation on summer okra yield was found to be substantial in semi-arid regions. Although okra exhibits significant tolerance to drought, it requires substantial quantities of water during its growth phase. Insufficient water availability adversely impacts the crop's output. In a study by Abd El-Kader et al. (2010), the greatest reduction in crop output was observed when there was a persistent and uninterrupted scarcity of water, which persisted until the initial harvest.

The findings of this study demonstrated a notable decrease in above-ground dry matter due to the reduction in irrigation, which aligns with previous reports (Stone et al., 2001). In a study by Cakir (2004), during the rapid growth phase of maize, a temporary state of dryness resulted in a significant decrease of 28% to 32% in the above-ground biomass. Conversely, excessive watering might result in a decrease in dry matter of above-ground plant components.

The primary goal of agricultural irrigation is to optimise production while minimising water usage, which can be accomplished by implementing a suitable irrigation system (Zhang et al., 2008). Previous studies have indicated a negative correlation between irrigation amount and WUE (Kuscu and Demir, 2013; Kresovic et al., 2016). However, the findings of our study indicate that there was an initial rise in WUE followed by a subsequent drop as irrigation was increased while keeping nitrogen constant. Maximum WUE was attained with 1.00 E_{pan} (equivalent to 4.94 kg/m^3). The observed results can perhaps be attributed to the positive impact of enhanced irrigation on the optimal utilisation of light and heat resources (Payero et al., 2008). Consequently, this can lead to a notable increase in the accumulation of above-ground dry matter and overall crop output. Nevertheless, an overabundance of water supply can lead to an over-utilisation of light and heat, which in turn can cause prolonged vegetative development and a delay in reproductive growth. Additionally, excessive irrigation practices may have resulted in substantial deep percolation and subsequent nutrient leaching within the soil, thereby leading to a decline in okra crop productivity. The study by Payero et al. (2008) revealed that there was a nonlinear relationship between WUE and both seasonal ET_c and grain yield. Additionally, the study found that WUE exhibited greater sensitivity to irrigation practices during drought years. The utilisation of drip irrigation technology in this study enhanced the WUE of summer okra by mitigating soil evaporation and deep drainage, while facilitating even distribution of water and nutrients within the tillage layer. Furthermore, the application of fertiliser has an impact on the efficiency of water consumption. WUE was found to be maximised at a nitrogen rate of 150 kg/ha, while the irrigation volume remained constant.

Extensive research has been conducted to examine the impacts of varying irrigation and fertilisation levels on WUE. According to Mahdi et al. (2003), optimal WUE was achieved while irrigating with 80% of the crop's evapotranspiration (ET_c) and applying nitrogen at a rate ranging from 140 to 250 kg/ha. In a study by Lamm et al. (2004), it was shown that WUE of maize reached its maximum when irrigated with 75% of the crop's ET_c and treated with a nitrogen administration rate of 180 kg N/ha. The findings of this study indicate a correlation between irrigation amount and the growth of summer okra plants. Specifically, it was observed that the plant height initially increased and subsequently declined with increasing irrigation. These results align with prior research conducted by Caviglia et al. (2014) and Jia et al. (2014). In contrast to prior research, the findings of the current study indicate a decrease in plant height with increasing nitrogen levels. The observed variation in okra growth sensitivity to irrigation levels can be related to the diverse climatic conditions across different regions.

Profitability

Maximum net returns of 372 694 INR/ha and a B:C ratio of 4.0 were recorded with crop irrigation scheduled at 1.0 E_{pan} (I_2), and were significantly higher than that recorded for 1.25 E_{pan} (I_3) and 0.75 E_{pan} (I_1) (Fig. 3). While the net returns and B:C ratio of crop irrigation scheduled at 0.75 E_{pan} remained inferior to I_2 and I_3 treatments. The crop receiving 100% RDN (N_2) recorded a maximum net return (337 841 INR/ha) and a B:C of 3.72, followed by 297 290 INR/ha and B:C of 3.3 recorded with N_3 (125% RDN), which was statistically on par with N_4 (150% RDN), with net returns of 281 221 INR/ha and B:C of 3.2. The lowest net returns of 254 011 INR/ha and B:C of 3.0 were recorded with N_1 (75% RDN), and these returns were significantly lower than that achieved with N_2, N_3 and N_4 treatments. The reduction in the net returns was attributed to the marginal cost implication as well as the interactive effects of nitrogen.

The primary objective in the field of agriculture is to achieve economic advantages. This study demonstrated quadratic relationships between economic advantages and both irrigation and nitrogen levels. Under equivalent nitrogen levels, a decrease in irrigation has the potential to result in significant economic losses. The economic benefits exhibited a non-linear relationship with nitrogen quantity under identical irrigation conditions, initially increasing and subsequently decreasing. This finding suggests that economic benefits are not always proportional to fertilisation amount in all scenarios (He et al., 2014).

According to Li (2014), in the Jingtai zone of Gansu Province, China, the economic advantage of spring maize amplified with an upsurge in irrigation quantity below fertilisation levels of 450-225-150 (N-P_2O_5-K_2O) kg/ha, with the irrigation level of 468 mm yielding the highest economic benefit of 20.790 CNY/ha. The largest economic advantage in Egypt's sandy region was only 4 890 CNY/ha with fertilisation levels of 180-72-36 (N-P_2O_5-K_2O) kg/ha and 680 mm of irrigation (Xiang et al., 2015). The economic profits of summer okra are affected by both the volumes of irrigation and nitrogen applied.

Evaluation of optimized irrigation and nitrogen level combinations using RSM

Table 4 presents the statistical information of the experiment factors and measured parameters of okra cultivation according to the central composite design. Furthermore, regression equations for the response variables of yield, above-ground dry matter, plant height, water use efficiency, net returns, and B:C ratio of summer okra under different irrigation and nitrogen levels are provided in Table 5. These equations were derived to analyse the relationships between the variables. For drip-fertigated okra, the lower and maximum limits of irrigation and nitrogen levels were set at 366 mm and 112.5 kg N/ha, respectively, and the upper limits were increased to 499 mm and 225 kg N/ha, respectively, to encompass ideal values. Table 6 provides a summary of the irrigation and nitrogen levels that correspond to each index's maximum value, showing a strong link between yield, above-ground dry matter and plant height. The inferences on first and second-order polynomials were derived based on the analysis of variance (ANOVA) conducted to assess the irrigation and nitrogen levels (factors) under optimization (Table 7). The quadratic curves obtained by RSM of relative yield, plant height, above-ground dry matter, WUE, net returns and B:C ratio against irrigation and nitrogen inputs were oval-shaped with an indistinguishable centre point giving the maximum value of the objective function. A response graph (optimum point) of the five indexes of yield, plant height, above-ground dry matter, WUE, net returns and B:C enabled further analysis (Fig. 5) When ET_c ranged from 418–442 mm and nitrogen ranged from 167.04–176.13 kg N/ha, the summer okra yield, above-ground dry matter, plant height, B:C, net returns, and WUE reached the maximum of their extreme values simultaneously. Economically, it suggests that using more fertiliser and irrigation while maintaining the yield price would necessitate using less nitrogen and irrigation to maximise profit. However, more irrigation and nitrogen can be used profitably if produce prices rise.

The *p*-values were used to evaluate each coefficient's significance, in order to comprehend the pattern of reciprocal interactions between the test variables. The significance of the associated coefficient increases with decreasing *p*. Model terms are considered significant when their *p*-values are <0.05. Three-dimensional representations of the response surface produced by the model show the link between independent and dependent variables (Fig. 4). The coefficients shown in Table 4 served as the foundation for the response surfaces. Two variables were kept at their respective zero levels (the centre value of the testing ranges),

Table 4. Statistical information of the experimental factors and measured parameters of okra cultivation according to the central composite design

Factor	Independent variable	Range	Mean	Standard deviation
x_1	Crop evapotranspiration (ETc)	336–499 mm	424.6	57.87
x_2	Nitrogen levels	112.5–225 kg N/ha	168.7	43.79
Response	**Dependent variable**	**Range**	**Mean**	**Standard deviation**
y_1	Plant height	49.2–64.5 cm	56.7 cm	4.95
y_2	Above-ground dry matter	4 094–6 724 kg/ha	5152	844.98
y_3	Yield	15 810–26 857 kg/ha	20 824.6	3 900.27
y_4	WUE	4.05–5.27 kg/m^3	4.18	0.77
y_5	B:C ratio	2.59–4.34	3.35	0.61
y_6	Net returns	194 457–413 444 INR/ha	292 591	77 317.52

Table 5. Regression equations for the response variables of yield, above-ground dry matter, plant height, water use efficiency, net returns and B:C ratio of summer okra under different irrigation and nitrogen levels

Response variable	Regression equations	R^2 (%)	*p*-value
Yield (kg/ha)	$-340\,413 + 1\,549\,I + 307\,\mathrm{N} - 1.752\,I^2 - 0.888\,N^2 - 0.003\,I \times N$	92.09	<0.001
above-ground dry matter (kg/ha)	$-74\,922 + 356.0\,I + 36.8\,N - 0.4040\,I^2 - 0.1154\,N^2 + 0.0042\,I \times N$	93.36	<0.001
Plant height (cm)	$-414.9 + 2.072\,I + 0.290\,N - 0.002385\,I^2 - 0.001007\,N^2 + 0.000147\,I \times N$	96.03	<0.001
Water use efficiency (kg/m^3)	$-44.6 + 0.2136\,I + 0.0596\,N - 0.000254\,I^2 - 0.000165\,N^2 - 0.000006\,I \times N$	90.23	<0.001
B:C ratio	$-54.17 + 0.2472\,I + 0.0492\,N - 0.000280\,I^2 - 0.000143\,N^2 - 0.000000\,I \times N$	91.89	<0.001
Net returns (INR/ha)	$-6\,893\,167 + 30\,833\,I + 6\,131\,N - 34.90\,I^2 - 17.76\,N^2 - 0.06\,I \times N$	91.96	<0.001

Table 6. Irrigation and nitrogen levels with maximum plant height, dry matter, yield, WUE, net returns and B:C ratio

Response objective	Crop ET_c	Nitrogen levels	Maximum response
Plant height	439.88 mm	176.13 kg/ha	66.3 cm
Above-ground dry matter	441.23 mm	167.04 kg/ha	6 709.1 kg/ha
Yield	441.23 mm	171.59 kg/ha	28 295 kg/ha
WUE	418.39 mm	172.72 kg/ha	5.26 kg/m^3
B:C ratio	441.23 mm	171.59 kg/ha	4.54
Net returns	441.23 mm	171.60 kg/ha	441 133 INR/ha

Table 7. Analysis of variance (ANOVA) for yield, net returns, B:C ratio, plant height, above-ground dry matter, and water use efficiency against varied irrigation and nitrogen levels

Source	ANOVA of yield (kg/ha)					ANOVA of net returns (INR/ha)					ANOVA of B:C ratio				
	DF	Adj SS	Adj MS	F-value	*p*-value	DF	Adj SS	Adj MS	F-value	*p*-value	DF	Adj SS	Adj MS	F-value	*p*-value
Model	5	154 102 048	30 820 410	13.98	0.003	5	60 469 530 567	12 093 906 113	13.72	0.003	5	3.81368	0.76274	13.6	0.003
Linear	2	39 148 646	19 574 323	8.88	0.016	2	14 478 191 332	7 239 095 666	8.21	0.019	2	0.79688	0.39844	7.1	0.026
I	1	38 412 613	38 412 613	17.42	0.006	1	14 232 291 255	14 232 291 255	16.15	0.007	1	0.78751	0.78751	14.04	0.01
N	1	736 034	736 034	0.33	0.584	1	245 900 077	245 900 077	0.28	0.616	1	0.00937	0.00937	0.17	0.697
Square	2	136 439 264	68 219 632	30.93	0.001	2	54 184 005 775	27 092 002 888	30.74	0.001	2	3.49976	1.74988	31.19	0.001
I^2	1	117 739 231	117 739 231	53.39	0.000	1	46 699 347 921	46 699 347 921	52.98	0.000	1	3.01172	3.01172	53.69	0.000
N^2	1	18 700 033	18 700 033	8.48	0.027	1	7 484 657 854	7 484 657 854	8.49	0.027	1	0.48803	0.48803	8.7	0.026
2-way interaction	1	585	585	0.00	0.988	1	266 642	266 642	0	0.987	1	0.00001	0.00001	0	0.992
$I \times N$	1	585	585	0.00	0.988	1	266 642	266 642	0	0.987	1	0.00001	0.00001	0	0.992
Error	6	13 231 846	2 205 308			6	5 288 457 515	881 409 586			6	0.33658	0.0561		
Total	11	167 333 895				11	65 757 988 082				11	4.15027			
Source	**ANOVA of plant height (cm)**					**ANOVA of above-ground dry matter (kg/ha)**					**ANOVA of water use efficiency (kg/m³)**				
	DF	Adj SS	Adj MS	F-value	*p*-value	DF	Adj SS	Adj MS	F-value	*p*-value	DF	Adj SS	Adj MS	F-value	*p*-value
Model	5	259.348	51.87	29.01	0.000	5	7 332 724	1 466 545	16.88	0.002	5	5.93144	1.18629	11.08	0.005
Linear	2	45.129	22.565	12.62	0.007	2	1 826 674	913 337	10.51	0.011	2	1.77254	0.88627	8.28	0.019
I	1	41.405	41.405	23.16	0.003	1	1 823 811	1 823 811	20.99	0.004	1	1.73457	1.73457	16.21	0.007
N	1	3.724	3.724	2.08	0.199	1	2 863	2 863	0.03	0.862	1	0.03797	0.03797	0.35	0.573
Square	2	242.136	121.068	67.71	0.000	2	6 574 931	3 287 465	37.84	0.000	2	3.11581	1.55791	14.56	0.005
I^2	1	218.052	218.052	121.94	0.000	1	6 259 030	6 259 030	72.04	0.000	1	2.47126	2.47126	23.09	0.003
N^2	1	24.083	24.083	13.47	0.010	1	315 901	315 901	3.64	0.105	1	0.64455	0.64455	6.02	0.05
2-way interaction	1	1.404	1.404	0.79	0.410	1	1 132	1 132	0.01	0.913	1	0.0023	0.0023	0.02	0.888
$I \times N$	1	1.404	1.404	0.79	0.410	1	1 132	1 132	0.01	0.913	1	0.0023	0.0023	0.02	0.888
Error	6	10.729	1.788			6	521 303	86 884			6	0.64217	0.10703		
Total	11	270.077				11	7 854 028				11	6.57361			

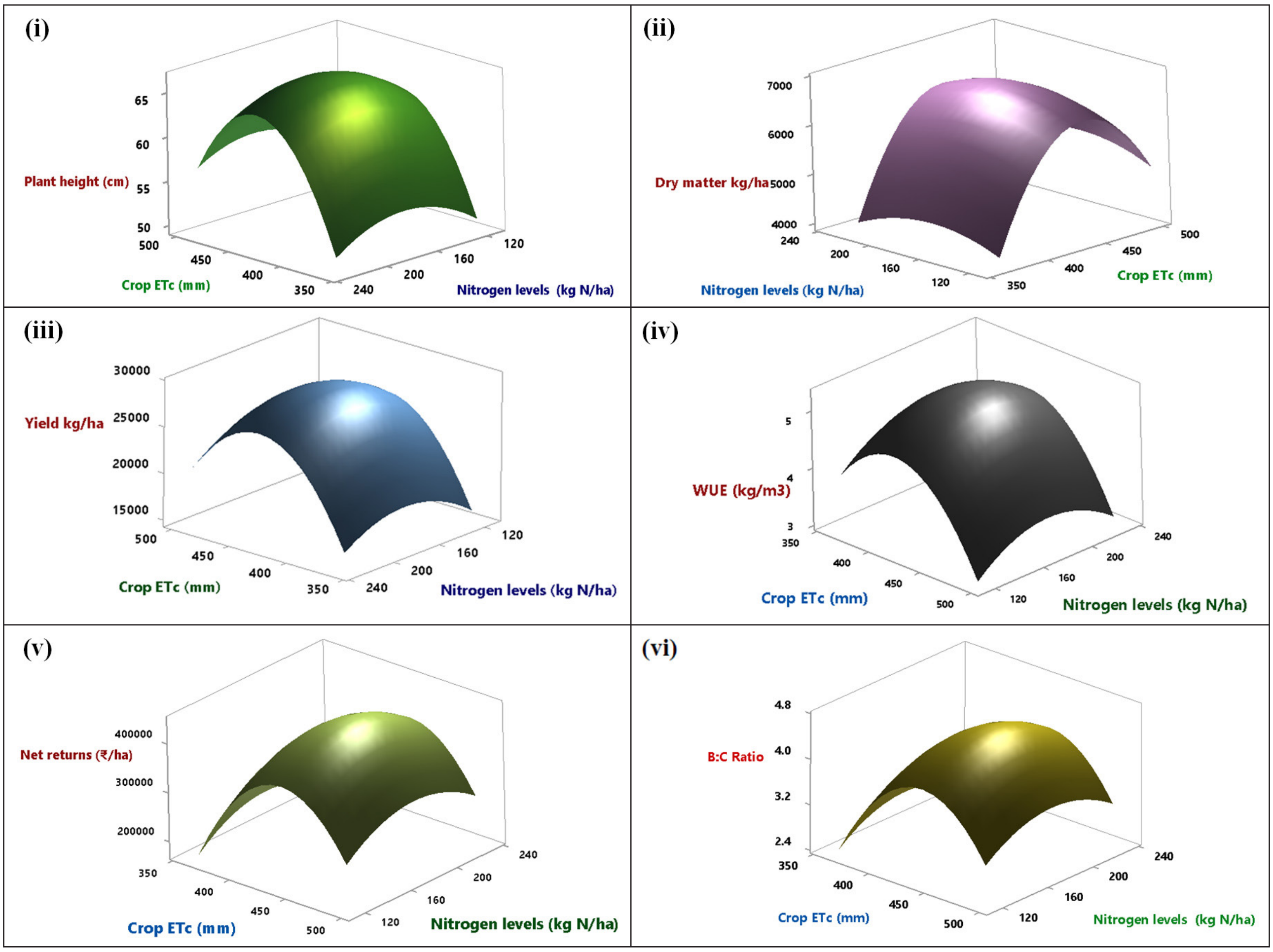

Figure 4. Relationship between okra plant height (i), above-ground dry matter (ii), yield (iii), water use efficiency (iv), net returns (v) and B:C ratio (vi) against varying irrigation and nitrogen levels. Note: The bright light on the surface of each plot indicates that the value increases correspondingly.

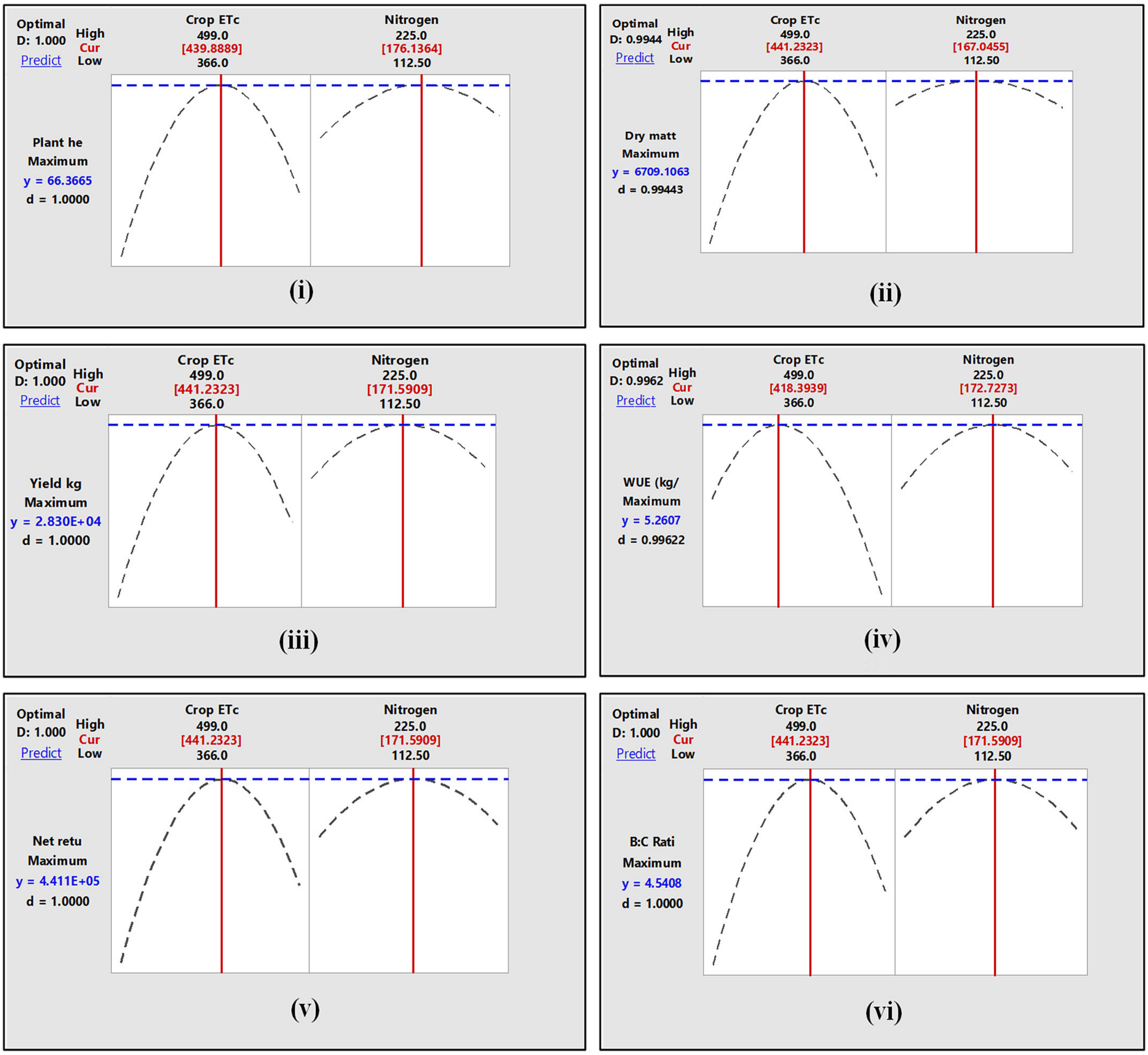

Figure 5. Response optimization of (i) okra plant height, (ii) above-ground dry matter, (iii) yield, (iv) water use efficiency, (v) net returns, and (vi) B:C ratio, against varied irrigation and nitrogen levels

and the other two were changed within the experimental range to produce the data. Exploration of the response surfaces generally revealed a complicated interplay between the variables. The response curves forecast an increase in production without taking into account the crucial distinction between the two treatments. It can be seen that the productivity, profitability and WUE of summer okra are affected by both irrigation and nitrogen applied.

The research discovered a downward convex shape in the three-dimensional relationship between yield, plant height, above-ground dry matter, WUE, net returns, and B:C ratio against irrigation and nitrogen levels (Fig. 4). As irrigation and fertilisation levels increased, these six indexes often initially increased and then decreased, which further supported the interaction effect of water and fertiliser on okra production, profitability and WUE, as shown in Table 4. In this study, irrigation of 441.23 mm and nitrogen of 171.60 kg N/ha were used to obtain the greatest net return of 441 133 INR/ha. This was because the crop water requirement could be met and over-irrigation may happen at high irrigation levels. Thus, in keeping with several earlier studies (Darshan et al., 2012; Tong and Guo, 2013), this non-linear relationship was described using quadratic functions.

CONCLUSIONS

The goal of the study was to determine the ideal production settings for okra. Process optimization was accomplished by applying response surface methodology to optimise operational conditions to enhance the okra crop yield Idea conditions were found using graphic response surfaces. Nitrogen and irrigation have a negative quadratic effect on okra yield. It was predicted that the optimum operating condition within the experimental range would be 418.39–441.23 mm irrigation water (ET_c) and 167.04–176.13 kg N/ha nitrogen supplied as urea. Okra production may be enhanced to yield 28 295 kg/ha under ideal conditions, enhancing the livelihood of Telangana's smallholder okra farmers and saving them additional input costs. Further research should be undertaken in which the methodology used in this study is applied to the rest of the production system, resulting in a clearer understanding of crop production as a whole.

AUTHOR CONTRIBUTIONS

C Lokesh: conceptualization, methodology, writing of initial draft, revision after review, data analysis, data collection and fieldwork.

B Balaji Naik: supervision, conceptualisation, methodology, review and editing. M Uma Devi and M Venkateswara Reddy: interpretation of results, methodology, review and editing.

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