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Soil-Matric-Potential-Based Irrigation Scheduling to Increase Yield and Water Productivity of Okra

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Abstract: A field experiment was conducted on okra (*Abelmoschus esculentus* L.) for assessing the sustainability of yield with optimum irrigation schedule based on soil moisture depletion. Four irrigation treatments: Irrigation at I_1:20%, I_2:30%, I_3:40% and I_4:50% of soil moisture depletion rate in main plots and three fertilizer treatments: Fertigation at F_1:100%, F_2:80% and F_3:60% of recommended NPK (100:25:40 kg/ha) in subplots were tested. Soil matric potential was recorded continuously using electronic tensiometers. The soil moisture characteristics curve was derived for various soil matric potential value sand the soil water content. The irrigation controller triggered solenoid valves for irrigation when soil moisture depletion reached a prespecified level in each treatment. Soil moisture depletion values were significantly predicted based on a regression model calibrated for each treatment over the crop growing period. The model gave minimum prediction error (PE) for I_1, followed by I_2, I_3 and I_4, respectively. Plant growth and yield parameters were significantly influenced by the soil moisture availability under each treatment. It is recommended that irrigation be scheduled at 20% soil moisture depletion rate together with 100% NPK fertilizer application for attaining sustainable yield of okra (12.3 t/ha), apart from maximum WUE (3.5 kg/m^3) and plant growth parameters under semiarid inceptisols.

Keywords: drip irrigation; fertigation; soil matric potential; tensiometer; regression; inceptisol

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1. Introduction

Okra is a very nutritive and tasty vegetable enriched with vitamins and minerals and is grown in many parts of India. India holds first position in okra production compared to other countries. The Agricultural and Processed Food Products Export Development Authority of India reported that India accounts for more than 60% of okra production of the world. Water-soluble nutrients in okra enable the immune system of the human body. Traditionally, irrigation scheduling is being practiced according to time-based or historic weather-based scheduling. Many studies were conducted on okra under drip irrigation to assess its water requirement based on a climatological approach. Based on this concept of irrigation scheduling, the availability of moisture in the soil is not considered, which is very much useful for plant growth.

Many researchers studied the effect of applying different doses of fertilizer through the broadcasting method on growth parameters and yield of okra [1–5], while few studies indicated the effect of fertilizer through drip fertigation. Under water stress conditions,

a significant reduction in leaf area, growth, plant height and yield in podded plants (one-time harvest) and depodded plants (frequent harvest) of okra was observed [6]. The crop water requirement was based on CROPWAT and 100, 80 and 60% of crop water requirement treatments were tested. Maximum growth, yield and root length were attained with 413 mm of water applied under 80% of water requirement [7]. The consumptive water use with low water application was observed as 296 mm based on a mini lysimeter study, where okra was irrigated at 50% water holding capacity [8].

Yield reduction was estimated up to 70% in three okra cultivars (Kano Dwarf, Lady Finger and Awgu Early) under moisture stress during the flowering and pod-filling stages, whereas minimum yield reduction was observed under moisture stress at the vegetative stage [9]. A moisture regime of 60% field capacity gave poor yield, growth parameters, leaf area, root length, shoot length and harvest index compared to 100% field capacity [10,11]. Maximum okra plant height, internodal length and fruit weight were attained under irrigation at 80% evapotranspiration with daily irrigation compared to 2 or 3 days interval irrigation [12]. Around 98% increased okra yield was attained under furrow irrigation with the 4 days interval and reduction in growth and yield parameters with furrow irrigation at the 12 days interval [13]. A study was conducted in okra with double- and single-row drip laterals geometry with 120, 100 and 80% recommended fertilizer and attained maximum yield when irrigated through single lateral geometry with 100% recommended fertilizers [14]. Maximum reduction in okra plant growth, yield and photosynthetic pigments were observed with drought stress at 50% level compared to low drought stress of 0 and 25% kept after 21 days of sowing [15]. Drought stress was induced at the vegetative, flowering and early pod-filling stages of okra, and it was observed that drought stress could be an indication for irrigation management practices [16].

Maximum nitrogen uptake (125 kg/ha) and yield were attained in drip-irrigated okra compared to sprinkler irrigation with 30% water saving [17]. Higher okra yield (1.4 t/ha), maximum root length and dry weight were attained in drip fertigation with 150:75:150 NPK kg/ha [18]. To provide irrigation based on soil moisture depletion, soil moisture should be assessed by soil matric potential. Tensiometers (Irrometer Company, Inc., Riverside, CA, USA) were used to measure soil matric potential, which is the pressure exerted by the plant roots to absorb soil moisture. Tensiometers are highly precise instruments to measure soil matric potential [19,20]. From soil matric potential observations, it is easy to understand the soil moisture distribution at the crop root zone. The soil moisture distribution pattern under drip irrigation was studied by researchers in different crops. Soil moisture under different drip lateral layouts like single-row, paired-row and microtube layouts in mulberry decreased with an increase in depth and distance from the dripping point [21]. Soil moisture distribution was assessed in drip-irrigated pea in fine sandy soil with a tensiometer-measured soil matric potential at -70, -75 and -85 kPa and found efficient distribution in the effective root zone depth compared to the top layer of soil [22].

Maximum moisture content was at the emitting point, which decreased with an increase in the distance from the dripper point [23]. Drip irrigation provided uniform distribution of water at the root zone of okra, which gave maximum yield with 45% water saving compared to a conventional irrigation system [24]. Uniform distribution of moisture at the effective root zone of okra ensured better yield and water productivity. Maximum yield (4.2 t/ha) and water use efficiency (8.1 kg/ha.mm) were attained in okra when drip irrigation was at 1.0 Epan and 120% of the recommended dose fertilizer application [25]. Fertigation enhances the nutrient availability at the root zone and thereby improved plant growth and yield. Higher plant growth and yield were attained under fertigation with 100% recommended fertilizer compared to conventional fertilizer application [26]. Maximum okra yield of 21 t/ha was attained with irrigation level at 125%ETc compared to 100, 75 and 50% ETc with maximum water use efficiency of 35 kg/ha.mm [27]. Maximum water use efficiency of 58 kg/ha.mm was observed under drip irrigation at 0.8 ET with plastic mulch compared to higher and lower ETc level [28].

In okra, water use efficiency of 8.8 kg/ha.mm was attained with irrigation at 40% crop water requirement, but 60% crop water requirement was recommended to attain good yield and water saving [28]. Irrigation at 1.0 ET produced maximum okra yield of 16 t/ha compared to lower ET levels with irrigation of 350 mm and attained maximum water use efficiency [28]. Maximum okra yield (7.8 t/ha) and water use efficiency were attained under modified bucket kit drip irrigation compared to water can application [29].

As the climatic variation affects crop ET, it is necessary to irrigate the crop as and when required [30,31]. Hence, irrigation should be based on soil moisture availability in order to save water and to increase water use efficiency. The stored moisture in the soil needs to be considered to schedule irrigation. The relative soil moisture availability can be represented by soil matric potential, which can be measured by tensiometers. Hence, soil-matric-potential-based irrigation is a very accurate practice to increase the yield and water use efficiency of okra. Hence, field research was carried out with the following objectives: (i) to determine the suitable soil moisture depletion level to schedule irrigation for okra, (ii) to determine the suitable fertilizer application rate with respect to yield and water use efficiency of okra in sandy loam soil under semiarid conditions.

2. Materials and Methods

2.1. Details of the Study

Research work was conducted at the Water Technology Centre, IARI, New Delhi during 2021 in sandy loam soil.Particle size distribution was determined by sieve analysis. Four samples were collected from different places of the field (at 0–15 cm; 15–30 cm and 30–45 cm depth), and the average values of particle sizes were considered to identify the soil type. The particle size distribution at the depth of 20–25 cm was 18% clay, 57% sand and 25% silt. The dry bulk density of the soil was 1.42 g·cm^{-3}. The soil profile consisted of less formed A, B and E horizons. Hence, as per USDA soil taxonomy, it was classified as inceptisol. The inceptisol horizon sequence was Ap–Bw–Bt. The field capacity and wilting point of the soil were estimated by a pressure plate apparatus. The field capacity was measured at the hydrolimits of 0.1 bar, and the wilting point was measured at the hydrolimits of 15 bar. At 0–15 cm, 15–30 cm and 30–45 cm depth, the field capacity was 24.35, 28.20 and 31.04 v/v, respectively. At 0–15 cm, 15–30 cm and 30–45 cm depth, the wilting point was 9.15, 11.32 and 12.81 v/v, respectively. The okra has maximum root density at the top 20 cm depth. Hence, the top layer field capacity was considered as a reference to schedule irrigation. Maximum and minimum mean temperatures were 36.2 and 21.3 °C, respectively, while rainfall of 129.5 mm was received during the crop growing period. The maximum and minimum mean relative humidity levels were 71.8 and 42.2%, respectively, while mean wind speed was 5.4 kmph during the season. Tensiometers were used to measure soil matric potential (SMP). There were 12 tensiometers installed in the field to measure soil matric potential. Volumetric soil moisture content was determined for different soil matric potential values. The experimental field had an area of 900 m^2. The location of the research field is given in Figure 1. After ploughing, Trichoderma viride was applied at one kg/ha to avoid fungal infection from soil. Okra (Pusa B-5 variety) seeds were treated with Trichoderma viride (produced at Indian Agricultural Research Institute) at 8 gm/kg and Pseudomonas flourescens (produced at Indian Agricultural Research Institute) at 10 gm/kg and dried under shade. Seeds were sown on raised beds of size 60 cm with a furrow size of 20 cm. Sowing was done by dibbling seeds at 40 cm × 20 cm spacing. Each raised bed has 2 rows with one lateral and population of 80 plants/raised bed. Critical irrigation was given to the entire plot. Each irrigation treatment had 6 raised beds of 8 m × 6 m length. Twelve treatment combinations of 4 irrigation and 3 fertigation levels were tested with 3 replications in a split-plot design. Irrigation levels were superimposed on the main plots, while fertigation levels were superimposed on the subplots.

The dry bulk density of undisturbed soil was determined by core cutter method at various depth. At 0–15 cm, 15–30 cm and 30–45 cm depth, the dry bulk density was 1.43, 1.47 and 1.38, respectively. The average value was considered as dry bulk density of the soil

in the research field. Tensiometers of size 30 cm were installed in each treatment to observe the soil matric potential at the effective root zone depth of 20–25 cm. Before the cropping period, soil samples were collected with a screw auger at the depth of 20–25 cm from six different places in the research field for various soil matric potential (SMP)values under wet moisture conditions. To arrive at the soil moisture characteristics curve, soil samples were collected to estimate soil moisture content at different matric potentials. The soil samples were collected for every 2 kpa difference, that is, from 10 to 46 kpa (like 10, 12, 14, 16, 18 kpa and so on). For each matric potential, 3 times the soil samples were collected at a time from the field, and this exercise was continued a number of times until the consistent values of moisture content against each matric potential were attained.
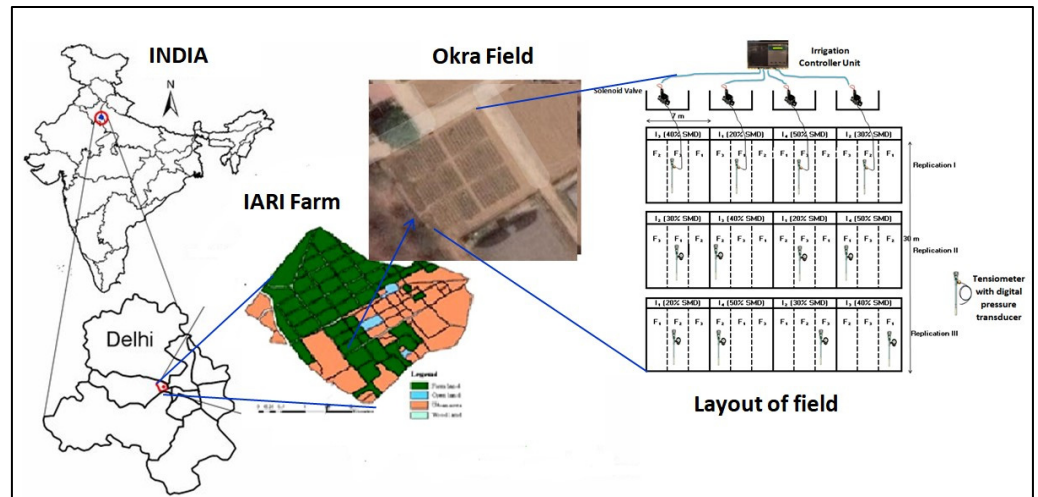

Figure 1. The location and sample plots of research field.

The soil samples of approx. 50 to 70 g weight were collected from the 20–30 cm depth with a screw auger and immediately kept in an oven to determine moisture content. The moisture content of the collected samples was estimated on a percentage basis by oven-dry method. This percentage moisture content was multiplied by the dry bulk density of the soil to estimate volumetric soil moisture content in terms of cm^3/cm^3. Then, the soil moisture characteristic curve was derived between volumetric moisture content and soil matric potential (Figure 2).
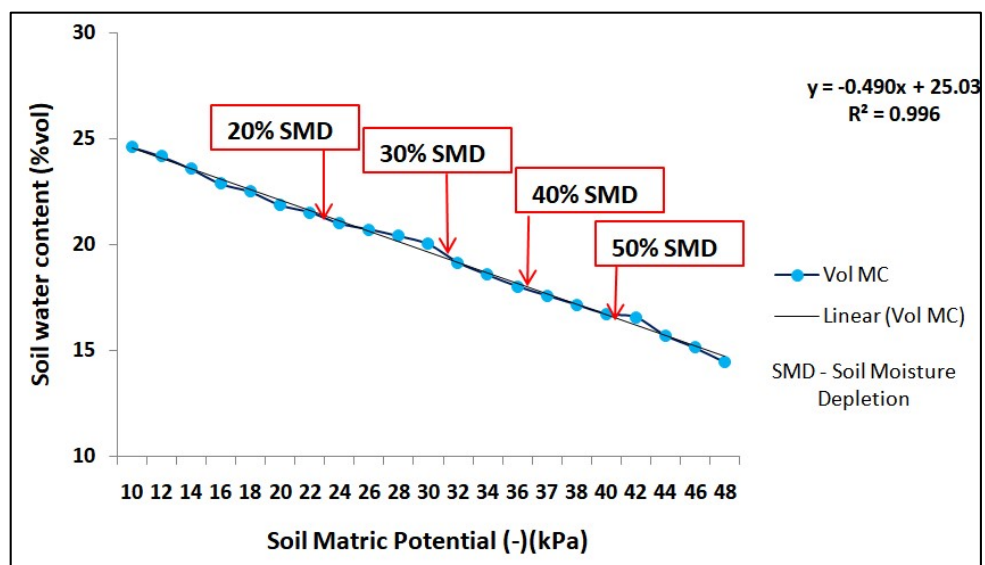

Figure 2. Soil moisture characteristic curve for the research field.

Soil moisture depletion (SMD) percentage was estimated based on the available moisture in the root zone at different soil matric potential levels. At −20 kPa SMP, soil moisture depletion (SMD) was 20%, and at −30, −35 and −40 kPa SMP, the moisture depletion was equal to 30, 40 and 50% of the available soil moisture at the effective root zone, respectively. The soil moisture characteristics curve for the research field is given in Figure 2.

The relationship between volumetric moisture content and soil matric potential was determined using the RETC model proposed by Van Genuchten (1980) [32]. The soil water retention curve for the research field was arrived at for the particular range of soil matric potential and not for the entire wilting point range. The soil water retention curve was drawn for the matric potential ranged from −10 kPa to −50 kPa only, as we have fixed the irrigation treatments in between a −20 to −40 kPa range of soil matric potential. The plotted readings were obtained from the soil samples taken from the field against each matric potential (observed values) and the fitted values derived from the RETC model. The soil moisture retention curve for the experimental field is given in Figure 3.
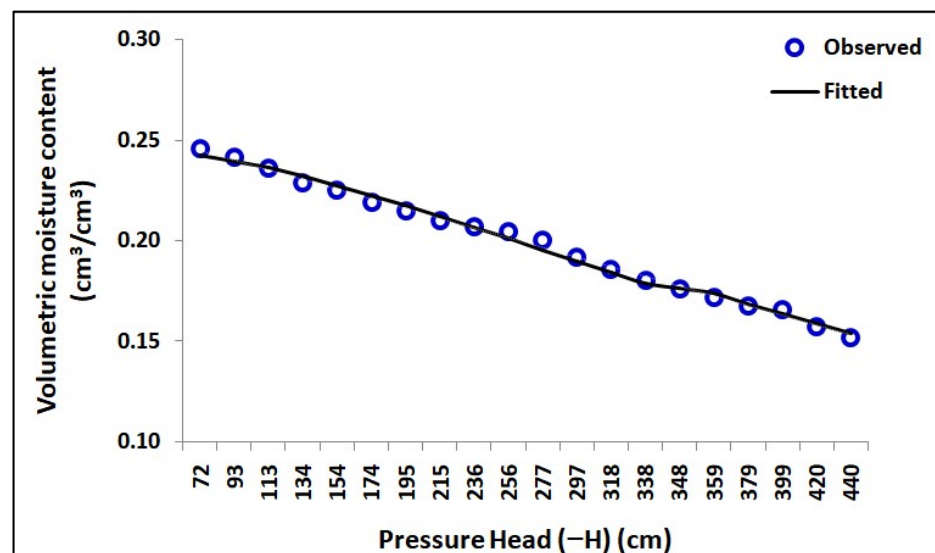

Figure 3. Soil moisture retention curve based on the observed and fitted values.

A program was predefined in an irrigation controller unit to start solenoid valves for irrigation whenever the specified soil moisture depletion was attained in four irrigation treatments (I$_1$:20%, I$_2$:30%, I$_3$:40% and I$_4$:50% of soil moisture depletion rate). There were three fertigation treatments (F$_1$:100%, F$_2$:80% and F$_3$:60% of recommended NPK (100:25:40 kg/ha)) given in five split doses. The irrigation treatments were superimposed 15 days after sowing based on the soil moisture depletion levels. Irrigation was started when the pre-specified soil moisture depletion level was reached. The amount of water was given in order to bring back the soil moisture to field capacity level.

2.2. Soil Moisture Distribution at Effective Root Zone Depth

Soil moisture distribution was assessed at different soil moisture depletion levels using Surfer 10.0 software. This software transforms 3-dimensional data and develops a contour plot. Moisture content data were given as input in XYZ coordinates format. The X-coordinate represented the radial distance from the emitter (near emitter, 15 and 30 cm distance), the Y-coordinate represented soil depth (10, 20 and 30 cm) and the Z-coordinate represented soil moisture. When the tensiometer showed SMP of −20, −30, −35 and −40 kPa (20%, 30%, 40% and 50% of soil moisture depletion), soil moisture samples were taken near the emitter point, 15 and 30 cm away from the emitter point at 10, 20 and 30 cm depth.

2.3. Okra Plant Growth and Yield Attributes

The plant height, number of branches/plant, leaf area index (LAI), number of pods/plant, 100 pods weight, number of seeds/pod of okra were observed. Five plants in each treatment were tagged randomly for observations. LAI was measured from each treatment (5 plants/replication) using an LAI 2000 LI-COR Plant canopy analyzer. Okra harvest started from the 60th day after sowing and continued every alternate day.

Water Use Efficiency (WUE)

Water use efficiency is the ratio between the produce yield obtained (kg) and the volume of water consumed (m^3) during the cropping season [33–35]. The efficiency of water use was calculated by the ratio of okra yield to the amount of water applied [36]. Water use efficiency was calculated between crop yield and water used and reported higher water use efficiency with a low water application rate [37]. Higher water use efficiency was registered with a higher yield of okra [38].

Water use efficiency (WUE) was determined for each treatment as

$$\text{WUE (kg/m}^3) = \frac{\text{Okra yield (kg)}}{\text{Volume of Water consumed during crop season (m}^3)} \tag{1}$$

Descriptive statistics were derived for plant growth and yield parameters. Analysis of variance (ANOVA) of data was carried out to assess the effects of irrigation, fertigation and their interaction based on a split-plot design [39]. Correlation coefficients and regression models were derived between yield and plant parameters and tested for significance based on coefficient of determination (R^2) and prediction error.

3. Results and Discussion

3.1. Fluctuation of Soil Matric Potential Values

In the okra field, the soil matric potential values fluctuated between −20 kPa and −11 kPa in I$_1$ treatment between two irrigations. When the soil moisture attained a 20% soil moisture depletion level, the particular treatment was irrigated automatically, and the soil moisture was brought back to the field capacity level. Similarly, when the soil moisture reached the 30%, 40% and 50% soil moisture depletion levels, the I$_2$, I$_3$ and I$_4$ treatments were irrigated, and the corresponding soil matric potential values ranged from −30 kPa to −11 kPa, −35 kPa to −11 kPa and −40 kPa to −11 kPa, respectively, throughout the crop growing season between irrigation cycles.

The daily soil matric potential variations were observed for 105 days from sowing to harvest of okra crop. Figure 4 shows the soil matric potential together with the rainfall and irrigation events.
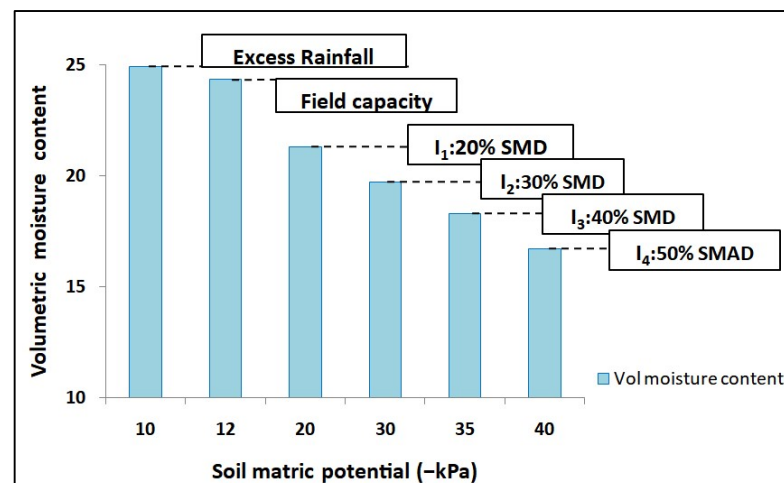
Figure 4. Soil matric potential together with rainfall and irrigation events.

The soil moisture available at the effective root zone depth of okra under different irrigation treatments during the crop season is given in Figure 5. In I_1 treatment when irrigation was scheduled at 20% SMD, the available soil water content was maintained at almost 90% of field capacity level. Similarly, in I_2, I_3 and I_4 treatments when irrigation was scheduled at 30%, 40% and 50% SMD, the available soil water content was maintained at 80%, 75% and 70% of field capacity level.

Figure 5. (**A–D**). Soil moisture available at the effective root zone depth of okra under different irrigation treatments during the crop season.

The descriptive statistics of the soil matric potential values as influenced by the four irrigation treatments are given in Table 1. Under I_1, the SMP values ranged from −22 to −10 with a mean of −15.990 (coefficient of variation of −21.2%), while the values ranged from −30 to −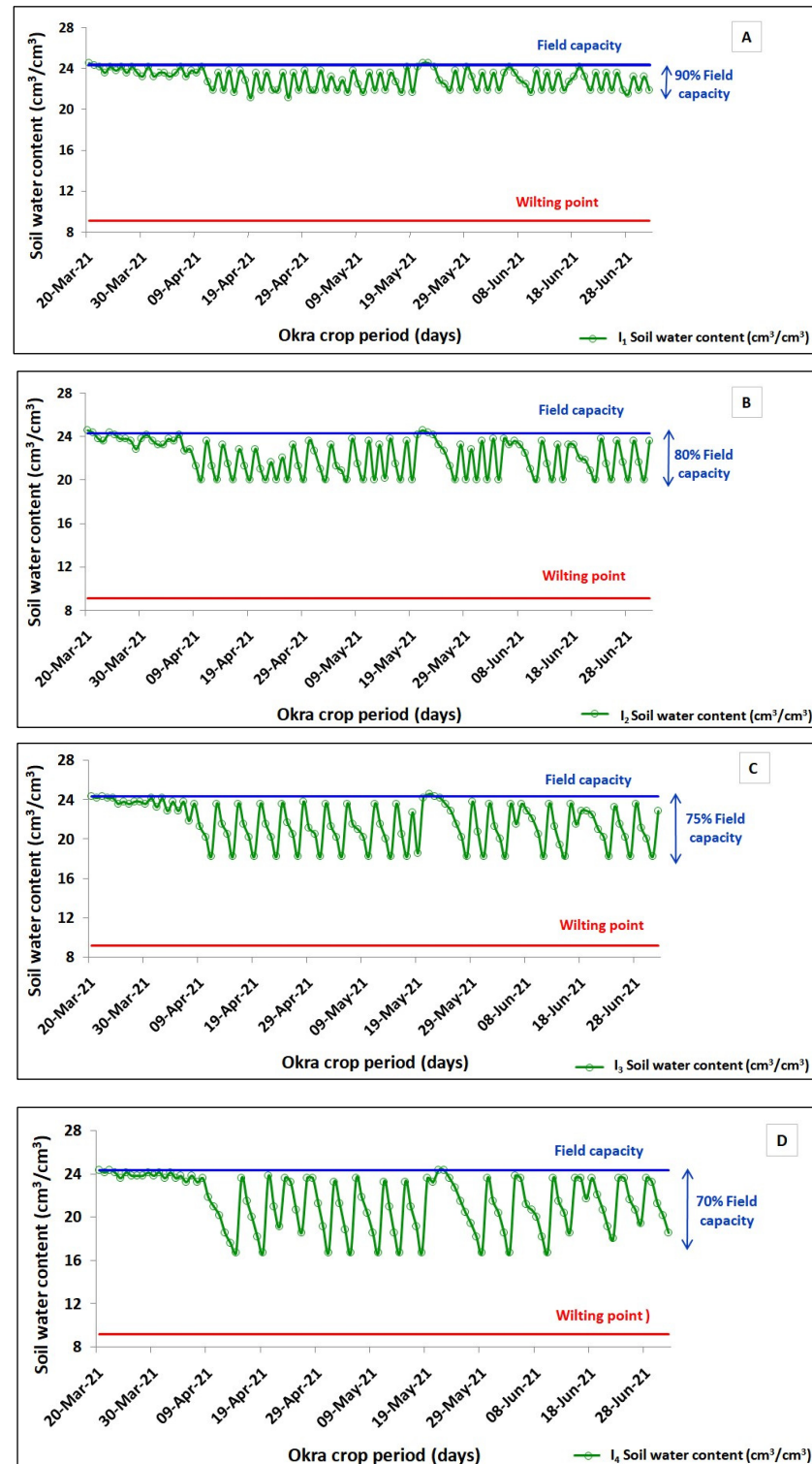10 with a mean of −21.705 (CV of −35.2%) under I_2. Similarly, the SMP values ranged from −35 to −10 with a mean of −21.705 (CV of −38.8%) under I_3, while the values ranged from −40 to −11 with a mean of −23.924 (CV of −42.3%) under I_4. Thus, I_4 had a wide range, maximum mean and CV (%), followed by I_3, I_2 and I_1, respectively.

Table 1. Descriptive statistics of effects of irrigation treatments on soil matric potential values from sowing to harvest of okra.

Statistic	I_1 (20% SMD)	I_2 (30% SMD)	I_3 (40% SMD)	I_4 (50% SMD)
Minimum SMP (kPa)	−22	−30	−35	−40
Maximum SMP (kPa)	−10	−10	−10	−11
Mean	−15.990	−19.800	−21.705	−23.924
Standard Deviation	3.390	6.962	8.431	10.129
Coefficient of Variation (%)	−21.2	−35.2	−38.8	−42.3

The fluctuations of soil matric potential values under each treatment were assessed for normality by grouping the 105 observations into 10 different classes, as described in Table 2. The differences between the observed and expected frequencies in different classes were tested based on Chi-square test at $p < 0.05$ and $p < 0.01$ levels of significance. The calculated Chi-square test values were more than the Chi-square critical values and indicated the best fit of normal distribution for the SMP data observed under all four treatments. The fluctuations of the SMP values in the four irrigation treatments in different classes are depicted in Figure 6.

Table 2. Testing of fluctuation of SMP values observed in irrigation treatments.

Treatments	Mean	SD	Lower Limit	Upper Limit	Observed	Expected
I_1	−15.990	−3.374		−20.8	9	8.083
			−20.8	−19.6	26	6.860
			−19.6	−18.4	1	9.998
			−18.4	−17.2	2	12.855
			−17.2	−16.0	3	14.585
			−16.0	−14.8	14	14.599
			−14.8	−13.6	24	12.894
			−13.6	−12.4	9	10.048
			−12.4	−11.2	13	6.908
			−11.2		4	8.169
					105	105
		Chi-square test statistic at 7 degrees of freedom			97.166	$p < 0.01$
I_2	−19.800	6.929		−30.0	26	7.402
			−30.0	−28.0	1	5.021
			−28.0	−26.0	1	7.049
			−26.0	−24.0	4	9.110
			−24.0	−22.0	10	10.839
			−22.0	−20.0	5	11.871
			−20.0	−18.0	3	11.970
			−18.0	−16.0	8	11.111
			−16.0	−14.0	27	9.495
			−14.0	−12.0	15	7.469
			−12.0	−10.0	5	5.409
			−10.0		0	8.255
					105	105
		Chi-square test statistic at 9 degrees of freedom			117.798	$p < 0.01$

Table 2. *Cont.*

Treatments	Mean	SD	Lower Limit	Upper Limit	Observed	Expected
I_3	−21.705	8.390		−35.0	18	5.936
			−35.0	−30.0	5	11.013
			−30.0	−27.5	8	8.764
			−27.5	−25.0	6	10.750
			−25.0	−22.5	6	12.074
			−22.5	−20.0	13	12.417
			−20.0	−17.5	2	11.693
			−17.5	−15.0	10	10.082
			−15.0	−12.5	26	7.960
			−12.5	−10.0	11	5.754
			−10.0		0	8.558
					105	105
		Chi-square test statistic at 8 degrees of freedom			95.313	$p < 0.01$
I_4	−23.924	10.080		−40.0	15	5.815
			−40.0	−34.2	5	10.355
			−34.2	−31.3	12	8.207
			−31.3	−28.4	6	10.116
			−28.4	−25.5	8	11.484
			−25.5	−22.6	7	12.009
			−22.6	−19.7	8	11.566
			−19.7	−16.8	3	10.261
			−16.8	−13.9	23	8.385
			−13.9	−11.0	18	6.311
			−11.0		0	10.490
					105	105
		Chi-square test statistic at 8 degrees of freedom			87.700	$p < 0.01$

Note(s): Chi-square critical value for 7 degrees of freedom at $p < 0.05$ level of significance = 14.067. Chi-square critical value for 7 degrees of freedom at $p < 0.01$ level of significance = 18.475. Chi-square critical value for 8 degrees of freedom at $p < 0.05$ level of significance = 15.507. Chi-square critical value for 8 degrees of freedom at $p < 0.01$ level of significance = 20.090. Chi-square critical value for 9 degrees of freedom at $p < 0.05$ level of significance = 16.919. Chi-square critical value for 9 degrees of freedom at $p < 0.01$ level of significance = 21.666.
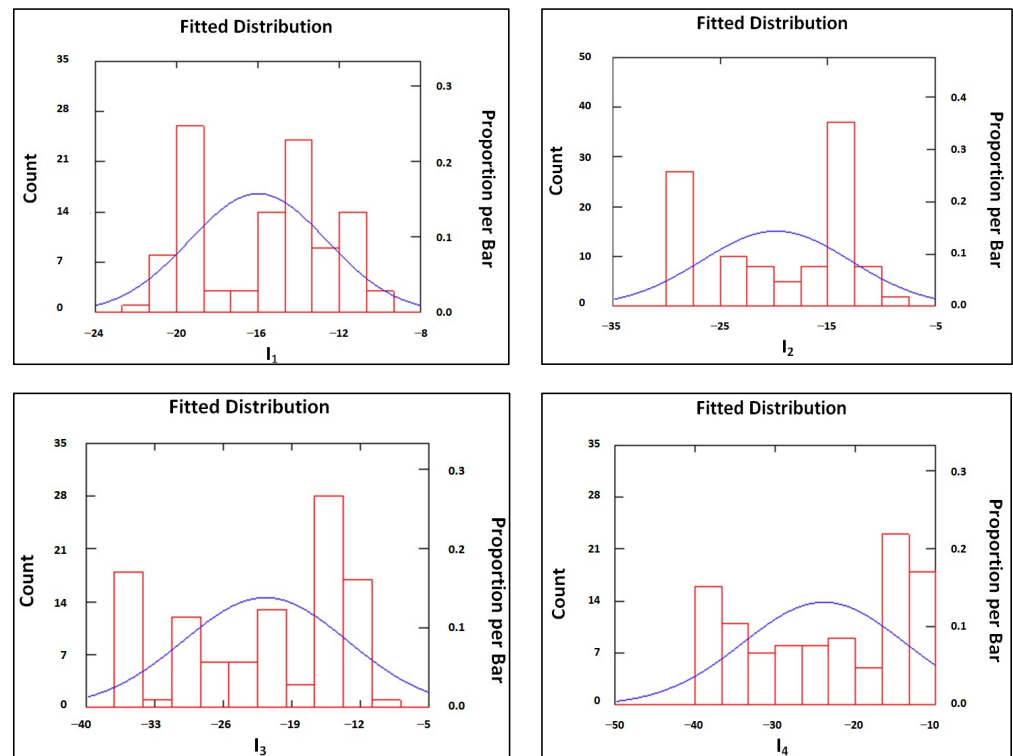

Figure 6. The fluctuation of the SMP values influenced by the irrigation treatments in different classes.

3.2. Assessment of Consistency and Reliability of Soil Matric Potential Values

Based on the relationships of soil matric potential values observed under different treatments, the four treatments were found to be positively and significantly related to each other. The relationship was maximum between I_3 and I_4 (0.620), followed by I_1 and I_2 (0.527), I_1 and I_4 (0.452), I_1 and I_3 (0.443), I_2 and I_3 (0.425) and I_2 and I_4 (0.321). Maximum and significant negative correlation was observed for I_4 (-0.325), followed by I_1 (-0.296), I_3 (-0.286) and I_2 (-0.234) over a period of time. The Cronbach values were determined between different pairs of treatments over a period of 105 days from sowing to harvest in order to assess the internal consistency and reliability of the changes that occurred in the SMP values. A Cronbach value of (i) more than 0.8 would indicate a high consistency and reliability, while (ii) a value between 0.5 and 0.8 would indicate moderate consistency and reliability, and (iii) a value less than 0.5 would indicate low consistency and reliability based on a comparison of treatments. When a set of two treatments were compared, maximum moderate reliability was observed between (i) I_3 and I_4 (0.757), followed by (ii) I_2 and I_3 (0.589) and (iii) I_1 and I_2 (0.587). However, the comparisons of (i) I_1 and I_3 (0.469), (ii) I_1 and I_4 (0.428), and (iii) I_2 and I_4 (0.461) indicated that the treatments had a low consistency and reliability over a period of time.

When a set of three treatments were compared, all the three comparisons of I_1, I_2 and I_3 (0.649), I_1, I_2 and I_4 (0.575), and (iii) I_2, I_3 and I_4 (0.712) indicated a moderate consistency and reliability of the SMP values. When a set of all four treatments were compared, the treatments were found to be moderately consistent and reliable with a Cronbach value of 0.729.
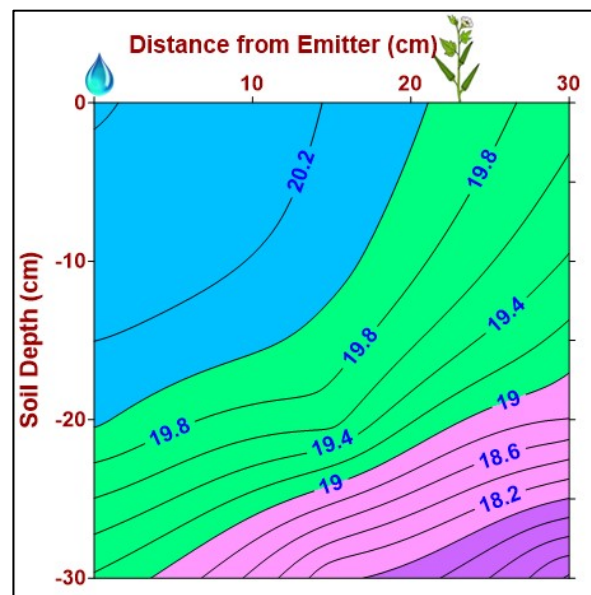
3.3. Soil Moisture Distribution Pattern under Drip Irrigation

At a 20% soil moisture depletion rate, soil moisture samples were collected near the emitter point, 15 cm and 30 cm away from the emitter point at a depth of 10, 20 and 30 cm. The soil moisture distribution pattern at different levels of soil moisture depletion rate (20%, 30% 40% and 50%) at different spatial distances and depths are depicted in Figure 7. Distribution of soil moisture was given in terms of volume basis. The graphical plots indicated that the moisture content decreased in deeper soil layers with increasing distance from the emitters. Higher moisture content was found at the top layer of the soil depth near the dripper point. Irrigation at 20% soil moisture depletion treatment maintained sufficient water content, followed by 30%, 40% and 50% soil moisture depletion rate treatments. Insufficient moisture distribution was found at irrigation at a 50% soil moisture depletion rate. With irrigation at 20% soil moisture depletion treatment, the level of moisture content ranged from 92% to 87% of field capacity from the dripper to 30 cm spatial distance and at the depth of 10–20 cm. With irrigation at 30% soil moisture depletion level treatment, about 83% to 77% of field capacity moisture content spread was found horizontally at the depth of 20 cm. There was a decreasing trend of moisture content at the deeper layer and the location away from the emitting point. With irrigation at40% moisture depletion treatment, the moisture content range at the effective root zone depth was 77% to 70% of field capacity from the dripper to 30 cm spatial distance. With irrigation at50% moisture depletion, the moisture content range at the effective root zone depth was 72% to 66% of field capacity from the dripper to 30 cm spatial distance. At the 20%, 30%, 40% and 50% soil moisture depletion levels, the moisture distribution was nearly 90%, 80%, 75% and 70% of the field capacity level, respectively.

Many studies were carried out on soil moisture distribution under drip-irrigated crops. Uniform distribution of soil moisture between soil depths of 15 to 37 cm in sandy loam soil at 30 cm dripper spacing was assessed with parallel contour lines plotted in Surfer 7.0 software with better uniformity of water spread [40]. The soil matric potential is decided by transporting irrigation water within the soil under a drip irrigation system [41]. The salt distribution in peas under a drip irrigation system was found to increase the soil salinity at the vertical distance from the dripper point and around the periphery of the wetted zone [42].
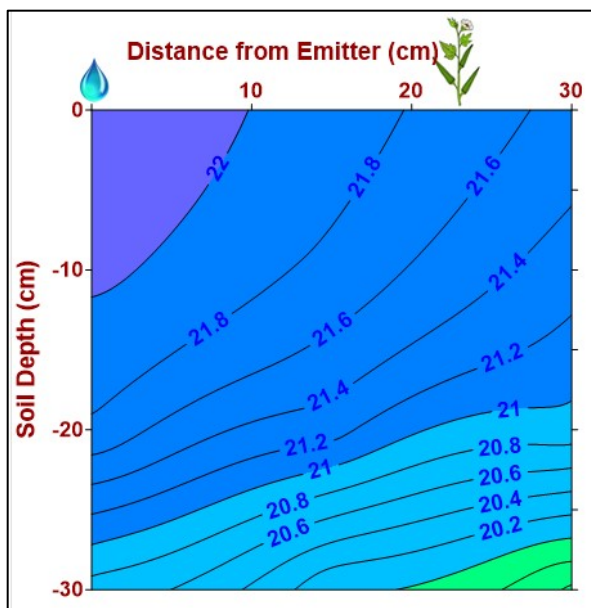
(**A**).Soil moisture distribution pattern at 20% of soil moisture depletion.

(**B**).Soil moisture distribution pattern at 30% of soil moisture depletion.
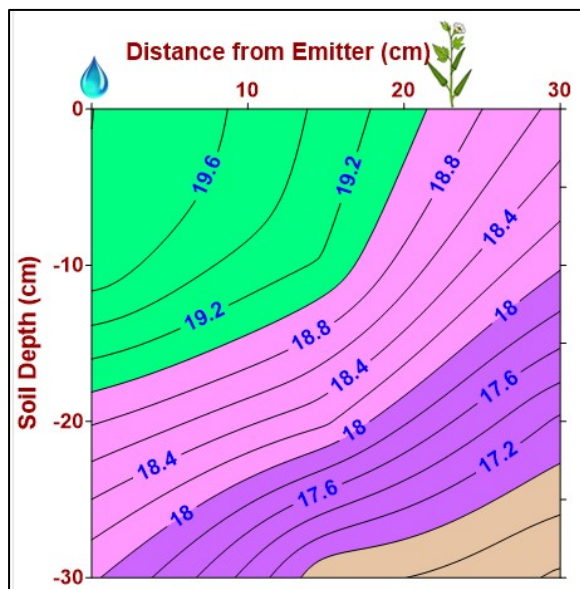
(**C**).Soil moisture distribution pattern at 40% of soil moisture depletion.
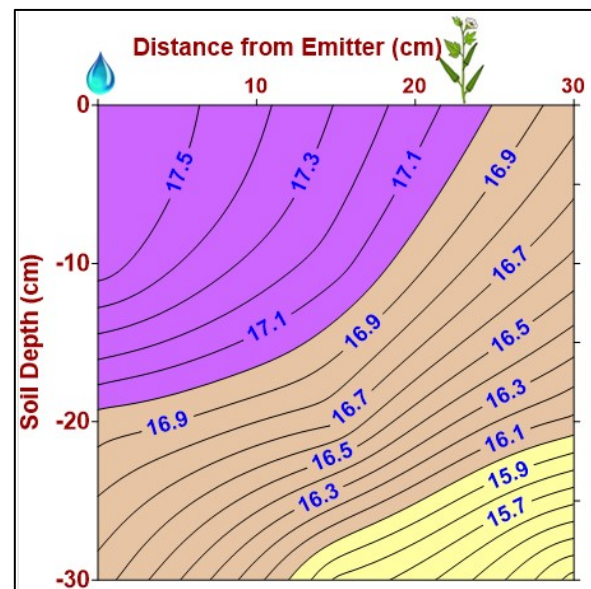
(**D**). Soil moisture distribution pattern at 50% of soil moisture depletion.

Figure 7. Soil moisture distribution in the okra field at different soil moisture depletion levels.

The fluctuation in moisture content at the effective root zone depth of okra under different treatments influenced the crop growth and yield parameters. Okra yield and growth parameters were found to be significant with irrigation at 25% soil moisture depletion level compared to 50% and 75% of soil moisture depletion level [43].

3.4. Irrigation Scheduling for Okra

Figure 8 depicts the irrigation depth and frequency applied during the crop growing season for the treatments of irrigation at 20%, 30%, 40% and 50% soil moisture depletion levels. An equal quantity of irrigation was applied till 20 days after the sowing of okra. The calculated amount of irrigation given per irrigation cycle in I_1 was 4.9 mm, I_2 was 8.7 mm,

I_3 was 12.1 mm and I_4 was 15.3 mm in order to bring the soil moisture closer to the field capacity level. During rainfall, the soil matric potential was below -10 kPa. Irrigation was not started until the pre-specified soil matric potential was reached in each irrigation treatment. The depth of water which satisfied the actual evapotranspiration was considered as effective rainfall. Similar findings were reported by applying an equal quantity of water with varying frequencies of irrigation in a drip-irrigated tomato crop [44]. The optimum soil moisture level in the root zone was maintained by the application of water through drip irrigation in tomato based on soil matric potential [19].
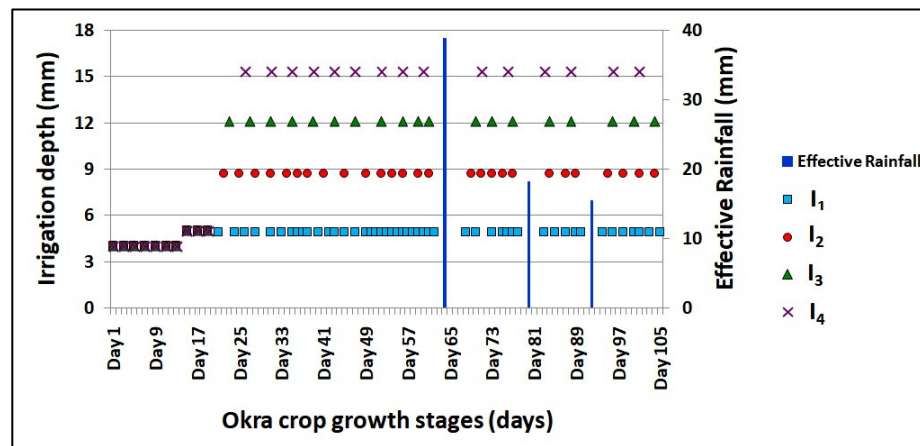

Figure 8. Depth and frequency of irrigation under I_1 (20% MAD), I_2 (30% MAD), I_3 (40% MAD) and I_4 (50% MAD) treatments in okra.

3.5. Effect of Irrigation and Fertigation on Okra Plant Parameters, Yield and Water Use Efficiency

The various plant growth parameters were observed in all the treatments. Increased plant height (123.6 cm), maximum number of fruiting branches (18), maximum number of flowers per plant (23), maximum number of fruits per plant (22), maximum 100 fruits weight (1.23 kg), maximum fruit length (14.6 cm), maximum fruit girth (6.4 cm) and maximum leaf area index (1.9) were observed in the treatment of irrigation at 20% soil moisture depletion with 100% of the recommended dose of fertilizers. Fewer plant growth parameters were observed in the treatment of irrigation scheduling at 50% soil moisture depletion level with 60% of the recommended dose of fertilizers as the frequency of irrigation was longer (Table 3). The plant might not obtain enough moisture and nutrients due to the unavailability of sufficient moisture at the root zone as the irrigation time interval was long. In less irrigation frequency treatments, it is not possible to maintain near-field-capacity moisture between successive irrigation treatments. The effects of various water application levels through drip irrigation with different nutrient requirements and fertilizer application methods were studied to determine the okra yield by many researchers [45–48].

Table 3. Growth parameters of okra and analysis of variance of effects of irrigation and fertilizer treatments.

Treatments	Plant Height (cm)	Number of Fruiting Branches per Plant	No. of Flowers per Plant	No. of Fruits per Plant	100 Fruits Weight (kg)	Length of Okra cm	Girth of Okra cm	LAI	Yield (t/ha)
I_1F_I	123.6	18	23	22	1.23	14.6	6.4	1.9	12.3
I_1F_2	101.5	14	19	17	1.09	12.8	6.0	1.7	9.5
I_1F_3	93.3	13	17	15	0.99	12.0	5.6	1.5	8.2
I_2F_1	110.9	17	21	19	1.12	13.1	6.1	1.8	10.4
I_2F_2	98.0	14	18	16	1.02	12.3	5.9	1.6	9.2
I_2F_3	93.5	11	16	14	0.99	11.5	5.4	1.4	8.0
I_3F_1	96.5	14	19	17	1.08	11.5	5.9	1.5	9.7

Table 3. *Cont.*

Treatments	Plant Height (cm)	Number of Fruiting Branches per Plant	No. of Flowers per Plant	No. of Fruits per Plant	100 Fruits Weight (kg)	Length of Okra cm	Girth of Okra cm	LAI	Yield (t/ha)
I_3F_2	93.8	12	17	15	1.03	10.9	5.8	1.4	8.7
I_3F_3	88.9	11	17	15	0.99	10.6	5.2	1.3	7.8
I_4F_1	96.6	13	17	16	1.05	11.7	5.4	1.5	9.2
I_4F_2	94.8	11	16	14	0.98	10.5	5.2	1.2	8.5
I_4F_3	87.6	10	16	13	0.95	9.7	5.2	1.2	7.5

A maximum okra yield of 12.3 t/ha was obtained in the treatment of irrigation scheduling at 20% soil moisture depletion level with 100% of the recommended dose of fertilizers, while a minimum yield of 7.5 t/ha was obtained in the treatment of irrigation scheduling at 50% of soil moisture depletion with 60% of the recommended dose of fertilizers. The minimum yield was due to non-uniform moisture availability because of a longer irrigation interval, thereby less nutrient uptake. Irrigation at 1.00 ET produced a maximum okra yield of 16 t/ha compared to lesser ET levels with a total irrigation quantity of 350 mm; however, it obtained maximum water use efficiency at lower ET levels [49]. Drip irrigation combined with mulches was tried in okra with different irrigation levels of 100%, 80% and 60% of net irrigation volume and obtained maximum yield in the treatment of irrigation at 100% of net irrigation volume with black plastic mulch [50]. Okra plant was irrigated based on leaf air temperature differential sensors, soil electrical conductivity sensors and evaluated leaf air temperature and soil moisture throughout the crop season [51]. Maximum okra yield was attained under sub-surface irrigation provided with 100% ETc, and the total application of water was 800 mm [52]. Maximum pea yield and water productivity were attained with the irrigation treatment scheduled at the soil matric potential level of −30 kPa [53]. The maximum number of fruits, fruit weight and yield of okra were influenced by the sowing time and hormone application in okra [54]. Higher fruit yield and maximum fertilizer use efficiency were recorded in okra when irrigation was at a 30% maximum allowable depletion level under sprinkler irrigation [55]. Maximum okra yield (24 t/ha) was obtained when irrigation was scheduled based on tensiometer reading compared to time-based irrigation [56]. Maximum water use efficiency (3.5 kg/m^3) was observed in the treatment of irrigation scheduled at 20% soil moisture depletion and supplied with 100% of the recommended dose of fertilizers in five split doses. The minimum water use efficiency (2.1 kg/m^3) was observed in irrigation scheduled at 50% soil moisture depletion and supplied with 60% of the recommended dose of fertilizers as okra yield was poor (Figure 9). Few studies were carried out to find out the water use efficiency of okra which confirmed this finding. The amount of water applied for okra under a drip irrigation system was around 500 mm and obtained a maximum water use efficiency of 8.1 kg/ha/mm with irrigation at 1.0 Epan with 120% of the recommended dose of fertilizers, but maximum agronomic efficiency (40.8 kg pod yield per kg of N applied) was obtained with a lower fertigation dose (60% of RDF) [25]. Okra crop was experimented with three different irrigation frequencies and obtained the highest water use efficiency (702 kg·ha^{-1}cm^{-1}) in the treatment of daily irrigation of 15 min [57]. The maximum water use efficiency (12.95 kg/m^3) was recorded in an automated water delivery system to okra compared to traditional water application with 11% water saving [58].

The descriptive statistics of yield and other plant parameters as influenced by different irrigation treatments are given in Table 4. The okra yield ranged from 7.2 to 12.5 t/ha with a mean of 9.1 t/ha (CV of 14.3%). I_1 was superior with a maximum mean yield of 10.0 t/ha (CV of 18.1%), while I_4 gave a minimum mean yield of 8.4 t/ha (CV of 9.2%). The water use efficiency ranged from 2.1 to 3.6 kg/m^3 with a mean of 2.6 kg/m^3 (CV of 14.0%). I_1 was superior with a maximum WUE of 2.8 kg/m^3 (CV of 18.4%), while I_4 gave a minimum mean WUE of 2.1 kg/m^3 (CV of 9.6%). The plant height ranged from 87.2 to 124.6 cm with a mean of 98.3 cm (CV of 9.9%). I_1 was superior with a maximum

mean plant height of 106.1 cm (CV of 12.8%), while I_4 gave a minimum mean plant height of 93.0 cm (CV of 4.5%). The number of fruiting branches/plant ranged from 9.8 to 18.4 with a mean of 13.1 (CV of 18.2%). I_1 was superior with a maximum mean number of fruiting branches/plant of 15 (CV of 16.5%), while I_4 gave a minimum number of fruiting branches/plant of 11.2 (CV of 12.0%).
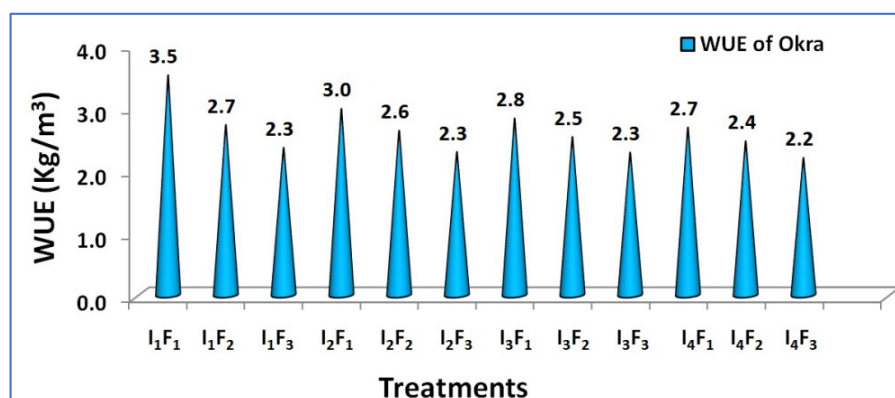

Figure 9. Water use efficiency under I_1 (20% MAD), I_2 (30% MAD), I_3 (40% MAD), I_4 (50% MAD) with F_1(100% RDF), F_2(80% RDF) and F_3(60% RDF) treatments in okra.

Table 4. Descriptive statistics of yield and other parameters as influenced by different irrigation treatments.

Parameter	Statistic	I_1	I_2	I_3	I_4	Pooled
Yield (t/ha)	Minimum	8.0	7.7	7.7	7.2	7.2
	Maximum	12.5	10.6	9.9	9.3	12.5
	Mean	10.0	9.2	8.7	8.4	9.1
	CV (%)	18.1	11.5	9.7	9.2	14.3
Water use efficiency (kg/m^3)	Minimum	2.3	2.2	2.2	2.1	2.1
	Maximum	3.6	3.0	2.9	2.7	3.6
	Mean	2.8	2.6	2.5	2.4	2.6
	CV (%)	18.4	11.4	9.7	9.6	14.0
Plant height (cm)	Minimum	92.4	93.0	87.6	87.2	87.2
	Maximum	124.6	112.0	97.8	97.0	124.6
	Mean	106.1	100.8	93.1	93.0	98.3
	CV (%)	12.8	7.8	3.8	4.5	9.9
No. of fruiting branches/plant	Minimum	12.4	11.0	10.8	9.8	9.8
	Maximum	18.4	17.0	14.2	13.2	18.4
	Mean	15.0	13.9	12.2	11.2	13.1
	CV (%)	16.5	17.0	11.4	12.0	18.2
No. of flowers/plant	Minimum	16.4	15.6	16.6	15.0	15.0
	Maximum	24.0	21.6	18.8	18.8	24.0
	Mean	19.6	18.4	17.6	16.4	18.0
	CV (%)	15.3	11.2	4.7	7.2	12.4
No. of fruits/plant	Minimum	14.4	12.8	13.8	13.0	12.8
	Maximum	22.8	20.0	16.8	17.2	22.8
	Mean	18.0	16.5	15.3	14.3	16.0
	CV (%)	17.5	15.1	7.8	10.2	15.8
100 fruit weight (kg)	Minimum	0.99	0.97	0.98	0.94	0.94
	Maximum	1.24	1.17	1.16	1.14	1.24
	Mean	1.11	1.05	1.03	0.99	1.04
	CV (%)	9.3	6.2	5.8	6.1	7.9
Length of okra (cm)	Minimum	11.7	11.3	10.4	9.6	9.6
	Maximum	14.7	13.2	12.0	11.8	14.7
	Mean	13.1	12.3	11.0	10.6	11.8
	CV (%)	9.1	5.8	4.5	8.1	11.2

Table 4. *Cont.*

Parameter	Statistic	I_1	I_2	I_3	I_4	Pooled
Girth of okra (cm)	Minimum	5.4	5.3	5.1	5.1	5.1
	Maximum	6.5	6.2	6.0	5.4	6.5
	Mean	6.0	5.8	5.6	5.2	5.7
	CV (%)	6.0	5.9	6.5	1.7	7.3
Leaf area index	Minimum	1.4	1.4	1.2	1.1	1.1
	Maximum	2.0	1.9	1.6	1.6	2.0
	Mean	1.7	1.6	1.4	1.3	1.5
	CV (%)	11.3	10.7	10.5	12.7	15.4

Note(s): CV: Coefficient of variation.

The number of flowers/plant ranged from 15 to 24 with a mean of 18 (CV of 12.4%). I_1 gave a maximum mean number of flowers/plant of 19.6 (CV of 15.3%), while I_4 gave a minimum number of flowers/plant of 16.4 (CV of 7.2%).The number of fruits/plant was in a range of 12.8 to 22.8 with a mean of 16.0 (CV of 15.8%). I_1 gave a maximum mean number of fruits/plant of 18.0 (CV of 17.5%), while I_4 gave a minimum number of fruits/plant of 14.3 (CV of 10.2%).The 100 fruit weight (kg) was ranged from 0.94 to 1.24 kg with a mean of 1.04 kg (CV of 7.9%). I_1 was superior with a maximum mean 100 fruit weight of 1.11 kg (CV of 9.3%), while I_4 gave a minimum fruit weight of 0.99 kg (CV of 6.1%).The length of okra was in the range of 9.6 to 14.7 cm with a mean of 11.8 cm (CV of 11.2%), while the girth of okra was in the range of 5.1 to 6.5 cm with a mean of 5.7 cm (CV of 7.3%). I_1 was superior for both length and girth of okra with a maximum mean length of 13.1 cm (CV of 9.1%) and girth of 6.0 cm (CV of 6.0%), while I_4 gave a minimum length of 10.6 cm (CV of 8.1%) and girth of 5.2 cm (CV of 1.7%), respectively. The leaf area index ranged from 1.1 to 2.0 with a mean of 1.5 (CV of 15.4%). I_1 was superior with a maximum mean LAI of 1.7 (CV of 11.3%), while I_4 gave a minimum LAI of 1.3 (CV of 12.7%). The study has indicated the superiority of application of irrigation at 20% soil moisture depletion with 100% of the recommended dose of fertilizers with a maximum mean okra yield and other plant parameters compared to 30%, 40% and 50% treatments.

The analysis of variance of the effects of irrigation in combination with fertilizer doses on yield and other plant parameters tested based on Snedecor's F-test are given in Table 5. There was a significant difference in the effects of irrigation and fertigation and their interaction on the plant height, number of fruiting branches/plant, number of flowers/plant, number of fruits/plant, 100 fruit weight, length of okra, girth of okra, leaf area index and yield. Based on the Least Significant Difference (LSD) criteria at $p < 0.05$ level of significance, the irrigation and fertilizer treatments which are significantly superior for different parameters have been identified.

Table 5. Analysis of variance of effects of irrigation and fertilizer treatments on yield and other parameters in okra.

Treatments	Plant Height (PH)	No. of Fruiting Branches/ Plant (NOFB)	No. of Flowers/ Plant (NOFL)	No. of Fruits/ Plant (NOFR)	100 Fruit Weight (100FW)	Length of Okra (LEN)	Girth of Okra (GIR)	Leaf Area Index (LAI)	Yield (Y)
I_1F_I	123.6	18	23	22	1.23	14.6	6.4	1.9	12.3
I_1F_2	101.5	14	19	17	1.09	12.8	6.0	1.7	9.5
I_1F_3	93.3	13	17	15	0.99	12.0	5.6	1.5	8.2
I_2F_1	110.9	17	21	19	1.12	13.1	6.1	1.8	10.4
I_2F_2	98.0	14	18	16	1.02	12.3	5.9	1.6	9.2
I_2F_3	93.5	11	16	14	0.99	11.5	5.4	1.4	8.0
I_3F_1	96.5	14	19	17	1.08	11.5	5.9	1.5	9.7

Table 5. *Cont.*

Treatments	Plant Height (PH)	No. of Fruiting Branches/ Plant (NOFB)	No. of Flowers/ Plant (NOFL)	No. of Fruits/ Plant (NOFR)	100 Fruit Weight (100FW)	Length of Okra (LEN)	Girth of Okra (GIR)	Leaf Area Index (LAI)	Yield (Y)
I_3F_2	93.8	12	17	15	1.03	10.9	5.8	1.4	8.7
I_3F_3	88.9	11	17	15	0.99	10.6	5.2	1.3	7.8
I_4F_1	96.6	13	17	16	1.05	11.7	5.4	1.5	9.2
I_4F_2	94.8	11	16	14	0.98	10.5	5.2	1.2	8.5
I_4F_3	87.6	10	16	13	0.95	9.7	5.2	1.2	7.5
Irrigation (I)	**	**	**	**	**	**	**	**	**
Fertilizer (F)	**	**	**	**	**	**	**	**	**
I × F	**	**	**	**	**	**	**	**	NS
LSD (I)	1.86	0.59	0.59	0.59	0.06	0.43	0.23	0.14	1.64
LSD (F)	1.00	0.36	0.36	0.36	0.04	0.28	0.08	0.06	NS
LSD (F at a level of I)	2.01	0.73	0.73	0.73	0.08	0.56	0.17	0.11	NS
LSD (I at a level of F)	2.79	0.96	0.96	0.96	0.11	0.72	0.29	0.18	NS

Note(s): PH: Plant height (cm). NOFB: No. of fruiting branches/plant. Y: Yield (t/ha). NOFL: No. of flowers/plant. NOFR: No. of fruits/plant. 100FW: 100 fruit weight (kg). LEN: Length of okra (cm). GIR: Girth of okra (cm). LAI: Leaf area index. ** indicates significance at $p < 0.01$ level. LSD—Least Significant Difference.

3.6. Relationship between Different Plant Parameters in Okra

The estimates of correlation between different plant parameters as influenced by the irrigation at different soil moisture depletion levels are given in Table 6. Okra yield had a significant correlation with all the plant parameters under all irrigation treatments except with (i) number of flowers under I_4, (ii) 100 fruit weight under I_3 and I_4, and (iii) LAI under I_3, while WUE had no significant correlation with (i) 100 fruit weight under I_4 and (ii) LAI under I_3. The plant height had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) number of flowers, number of fruits and 100 fruit weight under I_3 and I_4, and (ii) LAI under I_4. The number of fruit-yielding branches had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) 100 fruit weight and LAI under I_3. The number of flowers had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) 100 fruit weight under I_3 and I_4 and (ii) LAI under I_3. The number of fruits had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) 100 fruit weight under I_3 and I_4, (ii) girth of okra under I_3 and I_4, and (iii) LAI under I_3. The fruit weight had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) LAI under I_3 and I_4. The length of okra had a significant correlation with all the other plant parameters under all irrigation treatments except with (i) LAI under I_3, while the girth of okra had a significant correlation with all the other plant parameters under all irrigation treatments except with LAI under I_3 and I_4.

Table 6. Correlation between yield and plant parameters under different irrigation treatments in okra.

Parameter-1	Parameter-2	I_1	I_2	I_3	I_4	Pooled
Yield	WUE	0.999 **	0.997 **	0.898 **	0.994 **	0.987 **
	PH	0.984 **	0.934 **	0.864 **	0.915 **	0.942 **
	NOFB	0.988 **	0.973 **	0.959 **	0.942 **	0.945 **
	NOFL	0.942 **	0.883 **	0.863 **	0.628	0.902 **
	NOFR	0.963 **	0.940 **	0.855 **	0.795 *	0.934 **
	FW100	0.957 **	0.835 **	0.545	0.561	0.855 **
	LEN	0.985 **	0.923 **	0.769 *	0.904 **	0.865 **
	GIR	0.921 **	0.947 **	0.864 **	0.889 **	0.848 **
	LAI	0.835 **	0.918 **	0.613	0.689 *	0.792 **

Table 6. *Cont.*

Parameter-1	Parameter-2	I_1	I_2	I_3	I_4	Pooled
WUE	PH	0.986 **	0.937 **	0.911 **	0.902 **	0.936 **
	NOFB	0.989 **	0.967 **	0.886 **	0.950 **	0.928 **
	NOFL	0.938 **	0.883 **	0.796 *	0.689 *	0.894 **
	NOFR	0.957 **	0.936 **	0.704 *	0.832 **	0.915 **
	FW100	0.957 **	0.851 **	0.702 *	0.519	0.866 **
	LEN	0.985 **	0.913 **	0.823 **	0.901 **	0.848 **
	GIR	0.929 **	0.944 **	0.878 **	0.857 **	0.836 **
	LAI	0.831 **	0.903 **	0.510	0.698 *	0.763 **
PH	NOFB	0.992 **	0.959 **	0.826 **	0.868 **	0.936 **
	NOFL	0.920 **	0.903 **	0.651	0.452	0.884 **
	NOFR	0.949 **	0.928 **	0.637	0.663	0.912 **
	FW100	0.969 **	0.866 **	0.600	0.609	0.856 **
	LEN	0.971 **	0.925 **	0.759 *	0.886 **	0.904 **
	GIR	0.899 **	0.817 **	0.901 **	0.786 *	0.807 **
	LAI	0.864 **	0.965 **	0.679 *	0.645	0.838 **
NOFB	NOFL	0.952 **	0.950 **	0.956 **	0.731 *	0.927 **
	NOFR	0.972 **	0.981 **	0.895 **	0.888 **	0.961 **
	FW100	0.964 **	0.907 **	0.593	0.683 *	0.863 **
	LEN	0.977 **	0.961 **	0.790 *	0.961 **	0.930 **
	GIR	0.911 **	0.924 **	0.799 **	0.864 **	0.892 **
	LAI	0.827 **	0.946 **	0.507	0.760 *	0.872 **
NOFL	NOFB	0.986 **	0.981 **	0.905 **	0.883 **	0.974 **
	FW100	0.904 **	0.927 **	0.575	0.217	0.826 **
	LEN	0.939 **	0.898 **	0.745 *	0.688 *	0.854 **
	GIR	0.897 **	0.836 **	0.625	0.456	0.816 **
	LAI	0.786 *	0.884 **	0.363	0.681 *	0.791 **
NOFR	FW100	0.930 **	0.918 **	0.400	0.399	0.833 **
	LEN	0.941 **	0.928 **	0.719 *	0.884 **	0.885 **
	GIR	0.862 **	0.904 **	0.578	0.581	0.819 **
	LAI	0.804 **	0.928 **	0.611	0.859 **	0.847 **
FW100	LEN	0.932 **	0.861 **	0.895 **	0.668 *	0.826 **
	GIR	0.897 **	0.824 **	0.695 *	0.736 *	0.808 **
	LAI	0.918 **	0.791 *	0.014	0.404	0.702 **
LEN	GIR	0.957 **	0.894 **	0.781 *	0.788 *	0.855 **
	LAI	0.806 **	0.899 **	0.377	0.872 **	0.888 **
GIR	LAI	0.785 *	0.800 **	0.424	0.483	0.788 **

Note(s): * and ** indicate significance at $p < 0.05$ and $p < 0.01$ level of significance, respectively. Critical correlation value at $p < 0.05$ level of significance with 7 degrees of freedom = 0.666. Critical correlation value at $p < 0.01$ level of significance with 7 degrees of freedom = 0.798. Critical correlation value at $p < 0.05$ level of significance with 34 degrees of freedom = 0.331. Critical correlation value at $p < 0.01$ level of significance with 34 degrees of freedom = 0.426. WUE: Water use efficiency (kg/m^3). PH: Plant height (cm). NOFL: No. of flowers. NOFB: No. of fruiting branches. NOFR: No. of fruits. FW100: 100 fruit weight (kg). LEN: Length of okra (cm). GIR: Girth of okra (cm). LAI: Leaf area index.

3.7. Regression Models of Yield with Different Plant Parameters in Okra

The effects of different plant parameters on okra yield under different irrigation treatments were assessed based on the regression model of yield through each plant parameter and also with the pooled regression model of yield. The regression coefficients, along with the coefficient of determination (R^2) and prediction error (PE) values, are given in Table 7. The regression coefficients of all the plant parameters under all irrigation treatments indicating the effects of plant parameters on okra yield were found to be significant except for (i) the number of flowers/plant under I_4, (ii) 100 fruit weight under I_3 and I_4 and (iii) leaf area index under I_3. The predictability as indicated by the coefficient of determination was significant for all the plant parameters under all irrigation treatments except for (i) the number of flowers/plant under I_4, (ii) 100 fruit weight under I_3 and I_4 and (iii) leaf area index under I_3 and I_4. The prediction error of okra yield ranged from

0.092 t/ha under I_4 with the model of water use efficiency to 1.068 t/ha under I_1 with the model of leaf area index.

Table 7. Treatment-wise regression models of yield with different plant parameters in okra.

Parameter	Treatment	Regression Model	R^2	PE
Water use efficiency (kg/m^3)	I_1	Y = 0.133 + 3.469 ** (WUE)	0.998 **	0.093
	I_2	Y = -0.037 + 3.514 ** (WUE)	0.993 **	0.092
	I_3	Y = 0.889 + 3.114 ** (WUE)	0.806 **	0.398
	I_4	Y = 0.424 + 3.288 ** (WUE)	0.988 **	0.092
	Pooled	Y = −0.014 + 3.493 ** (WUE)	0.975 **	0.210
Plant height (cm)	I_1	Y = −3.909 ** + 0.131 ** (PH)	0.968 **	0.349
	I_2	Y = −3.422 + 0.125 ** (PH)	0.872 **	0.404
	I_3	Y = −10.721 * + 0.209 ** (PH)	0.746 **	0.456
	I_4	Y = −7.449 * + 0.170 ** (PH)	0.836 **	0.334
	Pooled	Y = −3.227 ** + 0.125 ** (PH)	0.887 **	0.441
No. of fruiting branches/plant	I_1	Y = −0.892 + 0.727 ** (NOFB)	0.976 **	0.298
	I_2	Y = 3.139 ** + 0.435 ** (NOFB)	0.947 **	0.259
	I_3	Y = 1.654 + 0.580 ** (NOFB)	0.920 **	0.256
	I_4	Y = 2.323 * + 0.539 ** (NOFB)	0.887 **	0.277
	Pooled	Y = 2.354 ** + 0.514 ** (NOFB)	0.893 **	0.429
No. of flowers/plant	I_1	Y = −1.154 + 0.569 ** (NOFL)	0.887 **	0.652
	I_2	Y = 0.877 + 0.452 ** (NOFL)	0.779 **	0.529
	I_3	Y = −6.757 + 0.882 ** (NOFL)	0.744 **	0.457
	I_4	Y = 1.629 + 0.413 (NOFL)	0.395	0.642
	Pooled	Y = −0.378 + 0.526 ** (NOFL)	0.814 **	0.567
No. of fruits/plant	I_1	Y = 0.015 + 0.556 ** (NOFR)	0.928 **	0.522
	I_2	Y = 2.612 * + 0.399 ** (NOFR)	0.884 **	0.385
	I_3	Y = −0.542 + 0.607 ** (NOFR)	0.731 **	0.469
	I_4	Y = 2.346 + 0.422 ** (NOFR)	0.631 **	0.501
	Pooled	Y = 1.406 ** + 0.479 ** (NOFR)	0.872 **	0.471
100 fruit weight (kg)	I_1	Y = −8.567 ** + 16.798 ** (FW100)	0.915 **	0.565
	I_2	Y = −5.076 + 13.642 ** (FW100)	0.697 **	0.620
	I_3	Y = 0.870 + 7.625 (FW100)	0.297	0.758
	I_4	Y = 1.323 + 7.126 (FW100)	0.315	0.683
	Pooled	Y = −4.960 ** + 13.451 ** (FW100)	0.731 **	0.682
Length of okra (cm)	I_1	Y = −9.597 ** + 1.492 ** (LEN)	0.969 **	0.339
	I_2	Y = −7.584 * + 1.363 ** (LEN)	0.852 **	0.434
	I_3	Y = −5.844 + 1.325 ** (LEN)	0.592 *	0.578
	I_4	Y = −0.172 + 0.806 ** (LEN)	0.817 **	0.353
	Pooled	Y = −1.010 + 0.857 ** (LEN)	0.748 **	0.660
Girth of okra (cm)	I_1	Y = −17.738 ** + 4.614 ** (GIR)	0.849 **	0.755
	I_2	Y = −7.677 ** + 2.900 ** (GIR)	0.897 **	0.361
	I_3	Y = −2.558 + 2.006 ** (GIR)	0.746 **	0.456
	I_4	Y = −32.443 ** + 7.786 ** (GIR)	0.791 **	0.377
	Pooled	Y = −6.002 ** + 2.657 ** (GIR)	0.720 **	0.695
Leaf area index	I_1	Y = −3.381 + 7.887 ** (LAI)	0.697 **	1.068
	I_2	Y = 0.140 + 5.602 ** (LAI)	0.842 **	0.448
	I_3	Y = 3.791 + 3.544 (LAI)	0.375	0.715
	I_4	Y = 4.207 * + 3.242 * (LAI)	0.475	0.598
	Pooled	Y = 2.431 ** + 4.433 ** (LAI)	0.627 **	0.802

Note(s): * and ** indicate significance at $p < 0.05$ and $p < 0.01$ level of significance, respectively. R^2: Coefficient of determination. PE: Prediction error (t/ha).

Significant relationships were found between yield and different plant parameters when the data were pooled over the four irrigation treatments tested in the study. The relationship (r-value) of okra yield with the number of fruiting branches/plant (r = 0.945) and length of okra (r = 0.865) are described in Figure 10 (top), and the girth of okra (r = 0.848) and water use efficiency (r = 0.987) pooled over different irrigation treatments are described in Figure 10 (bottom). The relationship of okra yield with the number of

flowers/plant (r = 0.902) and number of fruits/plant (r = 0.934) is described in Figure 11 (top), and 100 fruit weight (r = 0.855) and leaf area index (r = 0.792) pooled over different irrigation treatments are described in Figure 11 (bottom). The relationship of okra yield with the plant height (r = 0.942) is described in Figure 12.
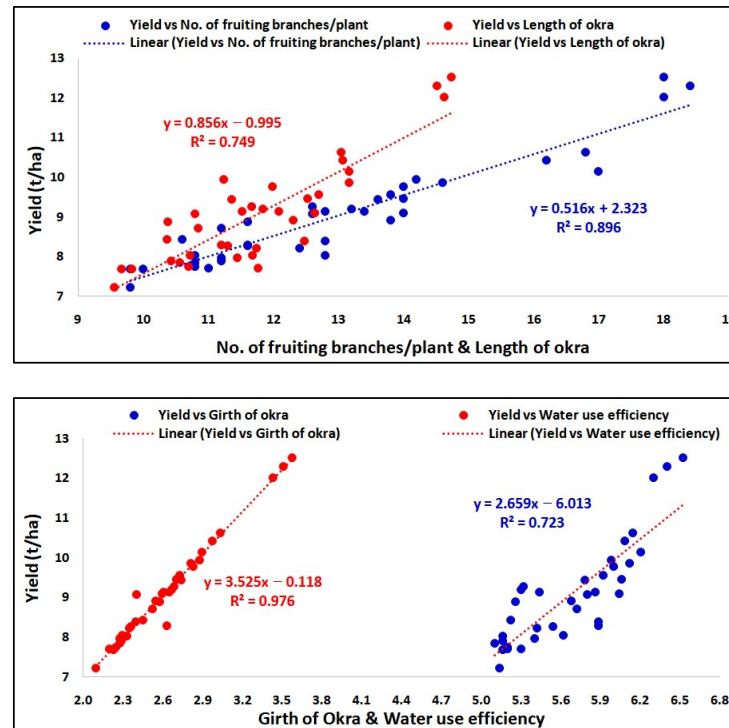

Figure 10. Relationship of okra yield with number of fruiting branches/plant and length of okra (cm) (**top**) and girth of okra (cm) and water use efficiency (**bottom**) pooled over different irrigation treatments.
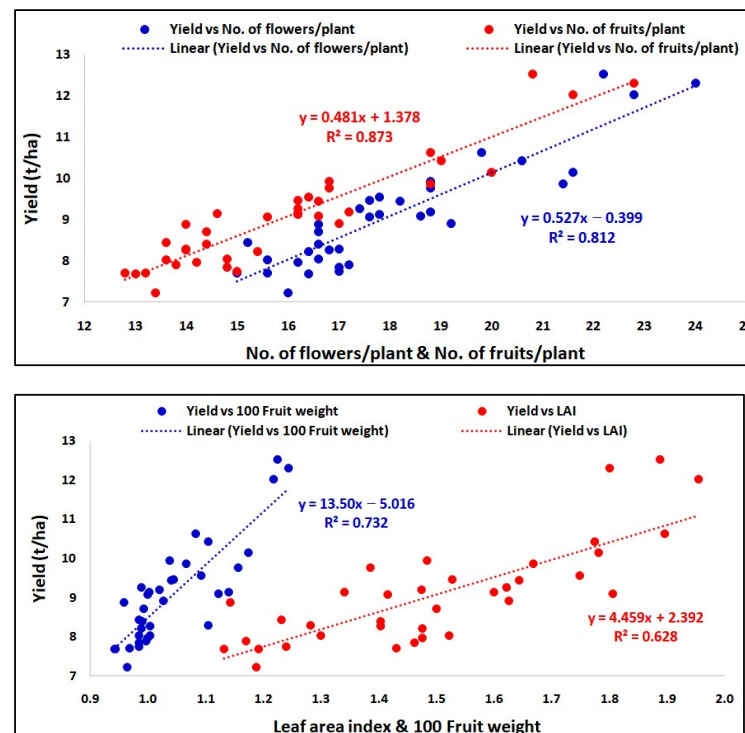
Figure 11. Relationship of okra yield with number of flowers/plant and number of fruits/plant (**top**) and 100 fruit weight and leaf area index (**bottom**) pooled over different irrigation treatments.
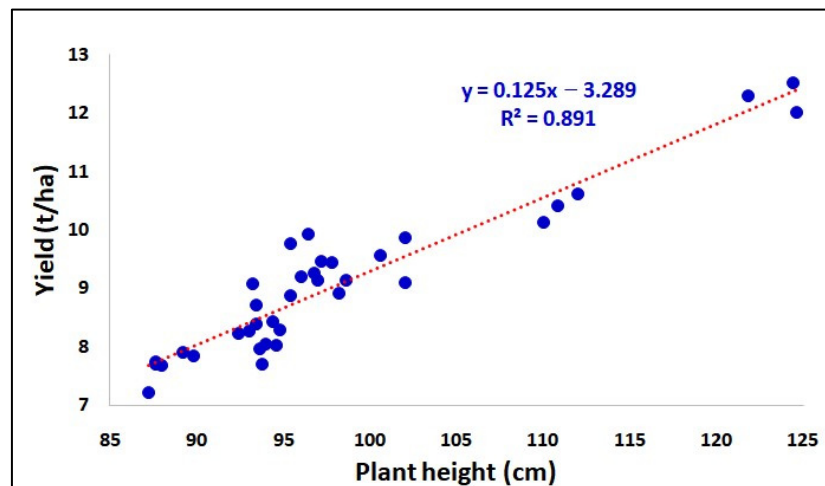
Figure 12. Relationship of okra yield with plant height pooled over different irrigation treatments.

3.8. Ranking of Different Treatments for Superiority of Okra Yield, Plant Parameters

Ranks were assigned to the 12 different treatment combinations of 4 levels of irrigation and 3 levels of fertilizer for their performance of okra yield and different plant parameters. Based on the ranks, the rank sum of each treatment was derived to identify the superior treatment with a minimum rank sum. Based on the rank sums, $I_1 F_1$ was superior with the lowest rank sum of 9, while $I_4 F_3$ attained the highest rank sum of 80. $I_2 F_1$ was the 2nd-best treatment with a rank sum of 18, while $I_1 F_2$ was the 3rd-best treatment with a rank sum of 28 based on the ranks assigned to different plant parameters. The rank sums of treatments based on the ranks assigned to okra yield and different plant parameters are described in Figure 13.
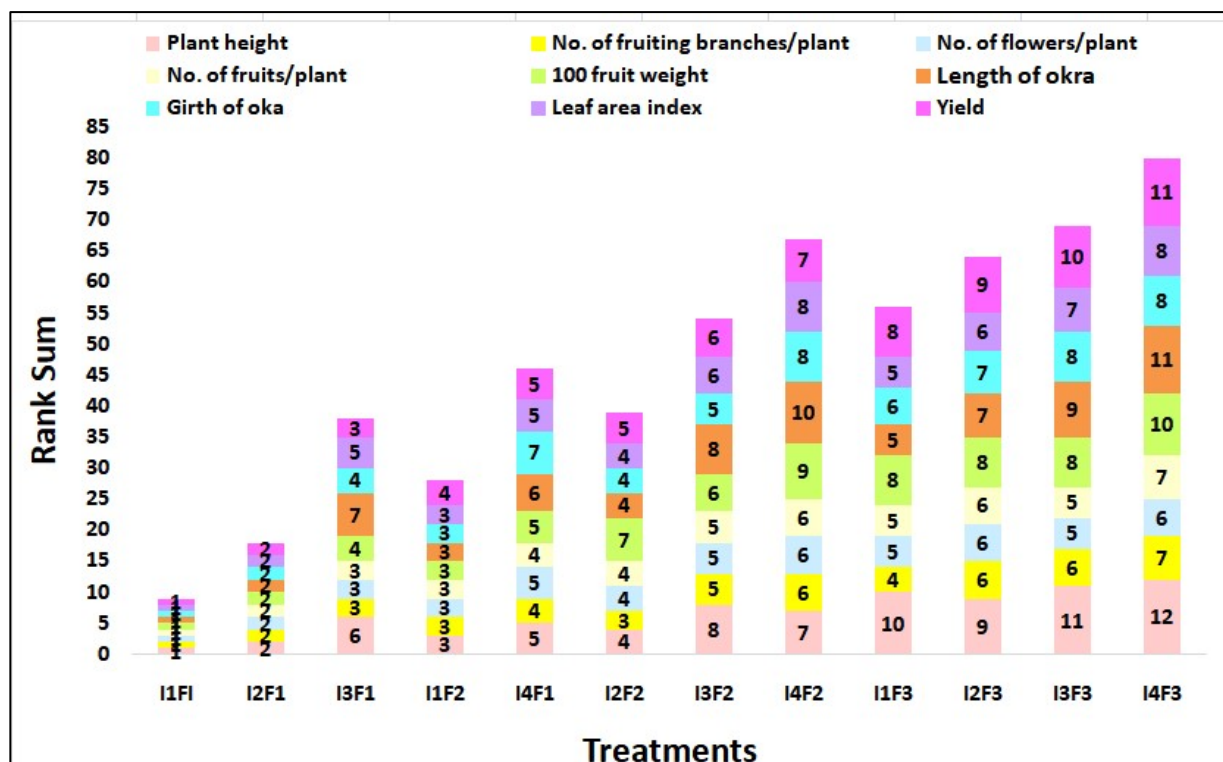
Figure 13. Rank sum of irrigation and fertigation treatments for assessing their superiority for okra yield and plant parameters.

The irrigation treatment I_1 was provided with sufficient soil moisture as the frequency of irrigation was higher. Among the four treatments, I_1 was the superior treatment with significantly higher okra yield and plant growth parameters. The analysis of variance indicated that I_1 was superior with a significantly higher mean yield and other plant parameters compared to other irrigation treatments. It had a maximum and significant correlation with yield and other plant parameters compared to I_2, I_3 and I_4 treatments. Based on the rank sums, the treatment I_1 in combination with F_1 was superior among different irrigation and fertilizer treatment combinations tested in the study. Similar findings were reported in okra whereby to achieve a higher yield, the soil moisture needs to be maintained at field capacity level with the dosage of application of 100% of the recommended dose of fertilizers [59]. The soil-moisture-based irrigation method provided sufficient moisture in the root zone, increased okra yield and saved adequate water [60].

4. Conclusions

The field study was conducted on okra with four irrigation and three fertigation treatments. Irrigation was scheduled based on soil moisture depletion at 20%, 30%, 40% and 50% together with fertilizer doses of 100%, 80% and 60% of recommended NPK (100:25:40 kg/ha). The soil matric potential fluctuations were observed continuously throughout the crop season by using electronic tensiometers. Uniform distribution of soil moisture between two successive irrigations was observed when irrigation was scheduled at a 20% soil moisture depletion rate. The moisture percentage was ranging from 92% to 87% of field capacity from the dripper point to 30 cm spatial distance at the effective root zone depth. Okra yield ranged from 7.2 to 12.5 t/ha with a mean of 9.1 t/ha, while water use efficiency ranged from 2.1 to 3.6 kg/m^3 with a mean of 2.6 kg/m^3. Cronbach alpha values indicated moderate reliability and consistency of the soil moisture depletion values under different irrigation treatments from sowing to harvest. Soil moisture depletion values were significantly predicted based on a regression model calibrated for each treatment. The model gave minimum prediction error (PE) for irrigation treatments. Irrigation scheduled at 20% soil moisture depletion together with 100% of the recommended dose of fertilizers gave significantly higher yield, plant height, number of fruiting branches/plant, number of flowers/plant, number of fruits, length and girth of okra with a minimum rank sum and significant correlation among parameters. The limitation of this study is that the research was conducted for one soil type and one vegetation season only, and the data were analyzed statistically. The same methodology should be tried for two or three vegetation seasons to validate the results. From this study, it is recommended to schedule irrigation at a 20% moisture depletion rate combined with 100% of the recommended fertilizers for attaining maximum returns from okra under inceptisols. Around 22 percent reductions in yield and water use efficiency were observed under 80% of the recommended dose of fertilizers through fertigation. However, to reduce the extreme usage of fertilizers, it is suggested to schedule irrigation at a 20% moisture depletion rate combined with 80% of the recommended dose of fertilizers.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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