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Effect of Drip Irrigation and Fertigation on Physical and Biochemical Parameters of Tomato under Protected Conditions

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Abstract

An experiment was conducted during 2024 under naturally ventilated polyhouse conditions at CSKHPKV, Palampur, to evaluate the effects of drip irrigation and stage-based fertigation on growth and quality of tomato. The study comprised two irrigation levels and six fertigation schedules arranged in a factorial completely randomized design. Higher irrigation level (I_2) significantly improved early flowering and picking, number of fruits per plant, fruit weight, soil moisture content and relative leaf water content, indicating better plant water status. Among fertigation treatments, F_5 (25% NK + 50% P basal and 75% NK + 50% P through) enhanced fruit number, fruit weight and quality attributes such as TSS, lycopene and total sugars. Lower irrigation (I_1) increased TSS, Lycopene content and total sugars. Overall, higher irrigation combined with balanced stage-based fertigation improved growth and fruit quality under protected cultivation.

Keywords: Fertigation, Irrigation, Protected Conditions, Tomato

Tomato (*Solanum lycopersicum* L.) is one of the most widely grown and economically significant vegetable crops worldwide, cultivated for both fresh consumption and processing. According to FAO[1], global tomato production reached about 192 million tonnes in 2023, reflecting a steady increase over the past decade and underscoring its growing contribution to global food and nutrition security. Tomato fruits are valued for their high yield potential and rich nutritional qualities, including carotenoids like lycopene, phenolic antioxidants and vitamins A and C, which play important roles in human health and diet quality[2].

In India, tomato is a key vegetable crop due to its high consumer demand and net returns. However, maintaining high productivity and fruit quality remains challenging due to water scarcity and poor nutrient management. Although India receives significant annual rainfall, its uneven distribution and increasing competition for water from domestic and industrial sectors necessitate the adoption of efficient irrigation methods. Moisture stress is a major constraint in tomato, as even short water deficits during flowering and fruit development can disrupt plant water relations, reduce photosynthesis and lower yield and fruit quality[3,4]. Furthermore, water stress can alter the accumulation of sugars, organic acids, vitamins and pigments, thereby affecting the nutritional quality and market value of tomato fruits. Protected cultivation systems such as greenhouses, polyhouses and net houses

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enhance tomato productivity by providing a controlled microclimate that reduces water losses and improves resource use efficiency[5]. Under these conditions, tomato plants generally produce higher yields and better fruit quality than in open fields; however, successful production depends on precise irrigation management and balanced nutrient supply according to crop growth stages[6]. Drip irrigation efficiently supplies water directly to the crop root zone, reducing evaporation, runoff and deep percolation losses while maintaining optimum soil moisture and improving water use efficiency[7,8]. When combined with fertigation, it enables precise application of soluble nutrients through irrigation water, enhancing nutrient availability and fertiliser use efficiency while minimising losses through leaching and volatilization[9]. Balanced application of nitrogen (N), phosphorus (P) and potassium (K) is essential for regulating plant growth, chlorophyll synthesis, enzymatic activity, flowering, fruit set and fruit quality[10,11]. Proper interaction between water and nutrients enhances physiological functions, promotes canopy development and improves crop productivity[12]. In high-value crops like tomato, where yield and chemical makeup impact profitability, optimising the relationship between nutrients and water is particularly critical. Recent studies highlight the importance of stage-wise irrigation and fertigation, as crop water and nutrient requirements vary across vegetative, flowering and fruiting stages[13,14]. Such targeted management improves physiological efficiency, enhances yield and improves fruit quality attributes such as total soluble solids, lycopene, vitamin C and antioxidant activity.

Despite extensive research on tomato irrigation and fertigation, limited information exists on the combined effects of different drip irrigation levels and stage-based fertigation on fruit physical and biochemical traits under protected cultivation. Therefore, optimising these practices according to crop growth stages is essential to improve physiological efficiency, fruit quality and resource use. This study evaluates the effects of drip irrigation and fertigation on the physical and biochemical characteristics of tomato under protected conditions.

MATERIALS AND METHODS

The study was conducted during 2024 at the experimental farm of CSKHPKV, Palampur, with tomato as a test crop in a polyhouse having natural ventilation with dimensions of 15 m length and 7 m width, covered with a plastic sheet. The experimental site was situated at 32°36′0″ N and 76°17′60″ E, having an altitude of 1290 m above mean sea level (msl). The region falls under the mid-hill zone of Himachal Pradesh and is characterised by a humid sub-temperate climate with mild summers and cool winters.

The seedlings of the Palam tomato hybrid-1 were transplanted on 10th April, 2024, with a plant spacing of 30 cm, and the experiment consisted of 2 irrigation and 6 fertigation schedules. The 12 treatment combinations were imposed in a factorial completely randomised design replicated three times. Each treatment was laid out in plots of 2.0 m length and 0.5 m width (1.0 m^2 area), ensuring uniform crop management and precise evaluation of irrigation and fertigation effects. The fertilizers applied at the rate of 184 kg N, 150 kg P_2O_5 and 110 kg K_2O per hectare and vermicompost was applied at the rate of 20 tonnes per hectare in each plot. The details of treatments are given in Table 1.

The changes in soil water content during the season at 0-7.5, 7.5-15, 15-22.5 and 22.5-30 cm depths were determined by the thermo-gravimetric method periodically during the crop growth period. The Relative Leaf Water Content (RLWC) for both crops was determined after transplanting at 30-day intervals. RLWC was computed from the fresh weight, turgid weight and oven dry weight according to the method given by Weatherly[15] as

$$\text{RLWC} = \frac{Fresh\ weight - Oven\ dry\ weight}{Fresh\ turgid\ weight - Oven\ dry\ weight} \times 100$$

Table 1. Treatment details

Irrigation levels					
I_1	0.6 ETc for first two months and 0.8 ETc thereafter				
I_2	0.8 ETc for first two months and 1.0 ETc thereafter				
Fertigation levels					
Treatments	**Basal**	**NPK fertigation**	**NPK fertigation schedule**		
			Week 4-6	**Week 7-9**	**Week 10-12**
N fertigation (F_1)	25 % N + 100 % PK	75 % N	20%N	40%N	15%N
NK fertigation (F_2)	25 % NK + 100 % P	75 % NK	20%NK	40%NK	15%NK
NPK fertigation 1 (F_3)	25 % NPK	75 % NPK	20%NK+30%P	40%NK+25%P	15%NK+20%P
NPK fertigation 2 (F_4)	50 % NPK	50 % NPK	15%NK+25%P	20%NK+15%P	15%NK+10%P
NPK fertigation 3 (F_5)	25 % NK + 50 % P	75 % NK + 50 % P	20%NK+25%P	40%NK+20%P	15%NK+5%P
NPK fertigation 4 (F_6)	50 % NK + 75 % P	50 % NK + 25 % P	15%NK+12.5%P	20%NK+7.5%P	15%NK+5%P

The total soluble solids content was determined with the help of 'Erma Hand Refractometer' under room temperature conditions (20°C) by putting a drop of juice on the prism and taking the reading[16]. The fully ripened tomato was used to estimate the lycopene content of the fruit. Lycopene content was estimated by using acetone and petroleum ether as suggested by Ranganna[16] and expressed in mg/100 g. Statistical analysis was done by using OPSTAT and R software, and Critical Difference (CD) was computed at the 5% level of significance for comparing treatment means.

RESULTS AND DISCUSSION

The data presented in Table 2 indicated that days to 50% flowering and first picking were significantly influenced by irrigation and fertigation levels, whereas their interaction was non-significant. Among irrigation levels, minimum days to 50% flowering (31.22 days) was observed under I_2, whereas maximum days (34.06 days) were observed under I_1. Among fertigation levels, the earliest flowering was observed under F_1 (30.67 days), which was statistically at par with F_6 (31.50 days), but significantly earlier than other treatments. The maximum days to 50% flowering (34.17 days) were recorded under F_3.

Days to first picking followed a similar trend to flowering. Irrigation levels significantly affected days to first picking. Among irrigation levels, I_2 resulted in earlier picking (68.33 days) compared to I_1 (71.33 days). Fertigation treatments also significantly influenced this parameter. The earliest picking or minimum days to first picking (67.83 days) was observed under F_1, followed by F_6 (68.33 days), whereas maximum delay (71.33 days) was recorded under F_3. The interaction effect was non-significant, indicating independent effects of irrigation and fertigation on crop maturity.

This can be attributed to the higher basal application of phosphorus and potassium, which enhance early root development, energy transfer (ATP synthesis) and meristem differentiation toward reproductive growth. Adequate phosphorus supports nucleic acid synthesis and accelerates floral initiation, while potassium improves carbohydrate translocation and hormonal regulation[17]. Moreover, the moderate basal nitrogen (25%) in F_1 likely prevented excessive vegetative growth. Higher nitrogen levels tend to

Table 2. Effect of drip irrigation and fertigation on crop growth parameters of tomato

Fertigation schedules	Days to 50% flowering			Days to first picking			Number of fruits per plant			Fruit weight		
	Irrigation schedules											
	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean
F_1	32.67	28.67	30.67	70.00	65.67	67.83	38.34	39.28	38.81	54.06	55.47	54.77
F_2	34.67	32.67	33.67	72.00	69.67	70.83	35.89	40.33	38.11	56.92	58.03	57.48
F_3	35.33	33.00	34.17	72.33	70.33	71.33	45.12	53.28	49.20	58.14	63.23	60.68
F_4	34.00	31.33	32.67	71.33	68.00	69.67	45.57	50.06	47.82	56.47	61.25	58.86
F_5	34.33	32.00	33.17	71.67	69.33	70.50	50.03	53.20	51.61	59.02	64.75	61.89
F_6	33.33	29.67	31.50	70.67	67.00	68.33	44.11	44.34	44.23	57.19	61.68	59.44
Mean	34.06	31.22		71.33	68.33		43.18	46.75		56.97	60.73	
Factors	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)
I	0.49	0.24	0.17	0.52	0.25	0.18	0.87	0.42	0.30	0.97	0.47	0.33
F	0.85	0.41	0.29	0.89	0.43	0.30	1.50	0.72	0.51	1.68	0.81	0.57
I×F	NS	0.58	0.41	NS	0.61	0.43	2.12	1.02	0.72	2.38	1.14	0.81

where, I_1- 0.6 ET_c for the first two months and 0.8 ET_c thereafter; I_2- 0.8 ET_c for the first two months and 1.0 ET_c thereafter; F_1- 25%N+100%PK basal and 75%N fertigation; F_2- 25%NK+100%P basal and 75%NKfertigation; F_3- 25%NPK basal and 75%NPK fertigation; F_4- 50%NPK basal and 50%NPK fertigation; F_5- 25%NK+50%P basal and 75%NK+50%P fertigation; F_6- 50%NK+75%P basal and 50%NK+25%P fertigation

delay flowering by promoting vegetative vigour[18]. Thus, balanced nutrient supply in F_1 favoured earlier reproductive transition and reduced days to flowering. The higher irrigation regime maintained optimum soil moisture, which enhanced nutrient mobility, root activity and hormonal signalling, thereby accelerating floral initiation and promoting earlier flowering[2].

The effect of irrigation, fertigation and their interaction had a significant effect on the number of fruits per plant (Table 2). Among irrigation levels, maximum number of fruits per plant (46.75) was recorded under I_2, whereas minimum (43.18) was recorded under I_1. Among fertigation treatments, maximum number of fruits per plant (51.61) was recorded under F_5, which was significantly superior to other treatments, followed by F_3 (49.20) and F_4 (47.82). Whereas, the lowest number of fruits per plant (38.11) was recorded under F_2. Among interactions, maximum number of fruits per plant (53.28) was recorded under I_2F_3, followed by I_2F_5 (53.20), while minimum (35.89) was observed under I_1F_2.

Fruit weight was also significantly influenced by irrigation, fertigation and their interaction (Table 2). Among irrigation schedules, I_2 recorded significantly higher fruit weight (60.73 g) compared to I_1 (56.97 g). Among fertigation treatments, maximum fruit weight (61.89 g) was observed under F_5 followed by F_3 (60.68 g), whereas minimum (54.77 g) was recorded under

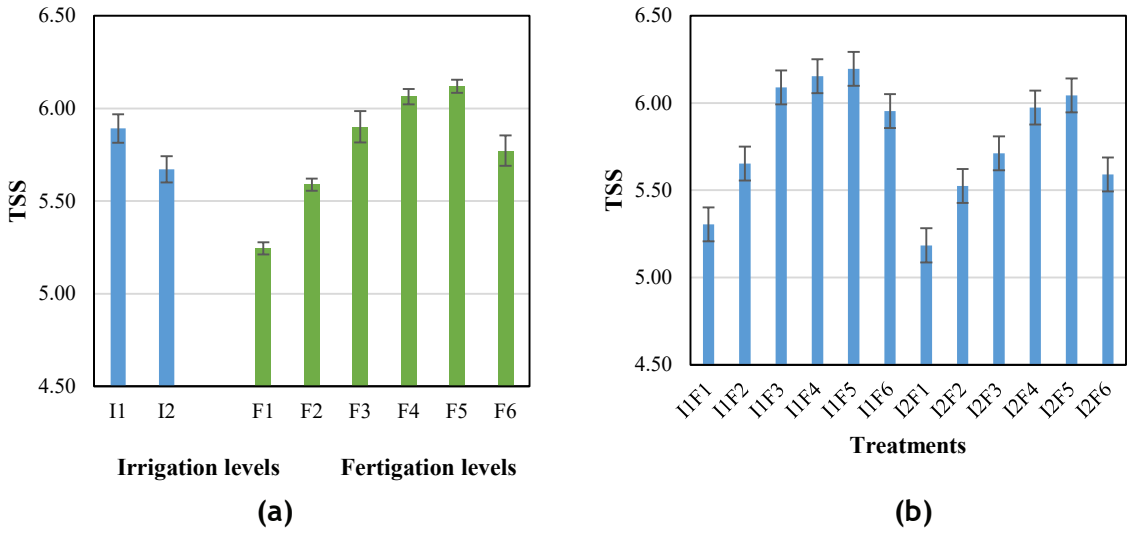


Figure 1. Effect of drip irrigation, fertigation **(a)** and their interaction **(b)** on TSS (°Brix) in tomato.

F_1. Among treatment combinations, the highest fruit weight (64.75 g) was recorded under I_2F_5 followed by I_2F_3 (63.23 g), whereas the lowest (54.06 g) was recorded under I_1F_1.

Higher irrigation coupled with balanced fertigation throughout the season ensured continuous moisture and nutrient availability during flowering and fruit development, thereby improving assimilate translocation to reproductive sinks and ultimately increasing both number of fruits per plant and fruit weight[2,19].

The fruit quality parameters of tomato were significantly influenced by irrigation, fertigation and their interactions. TSS showed a marked response to the treatments (Figure 1). Irrigation level I_1 recorded a mean TSS of 5.89 °Brix, which was significantly higher

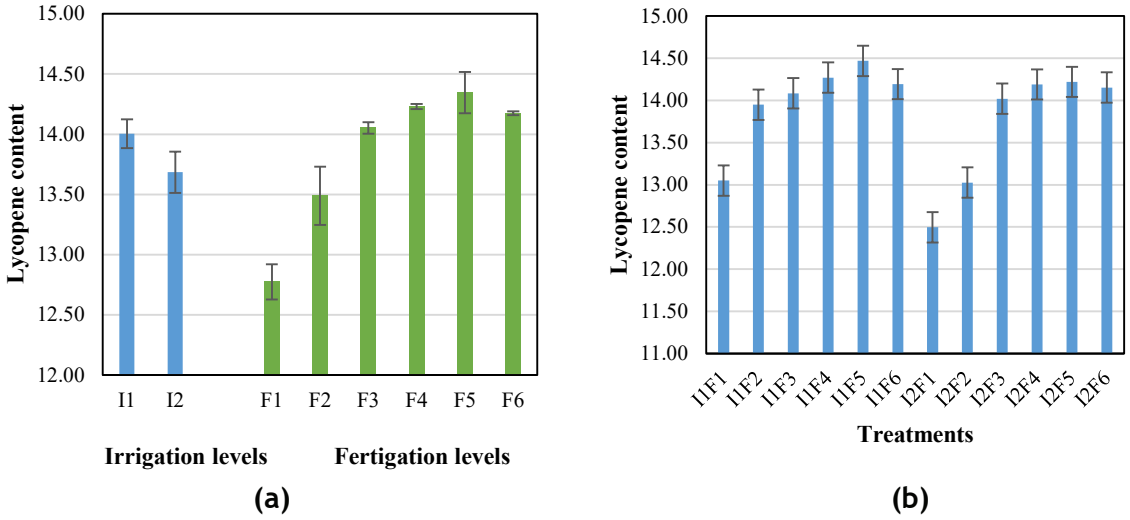


Figure 2. Effect of drip irrigation, fertigation **(a)** and their interaction **(b)** on lycopene content (mg/100g) in tomato.

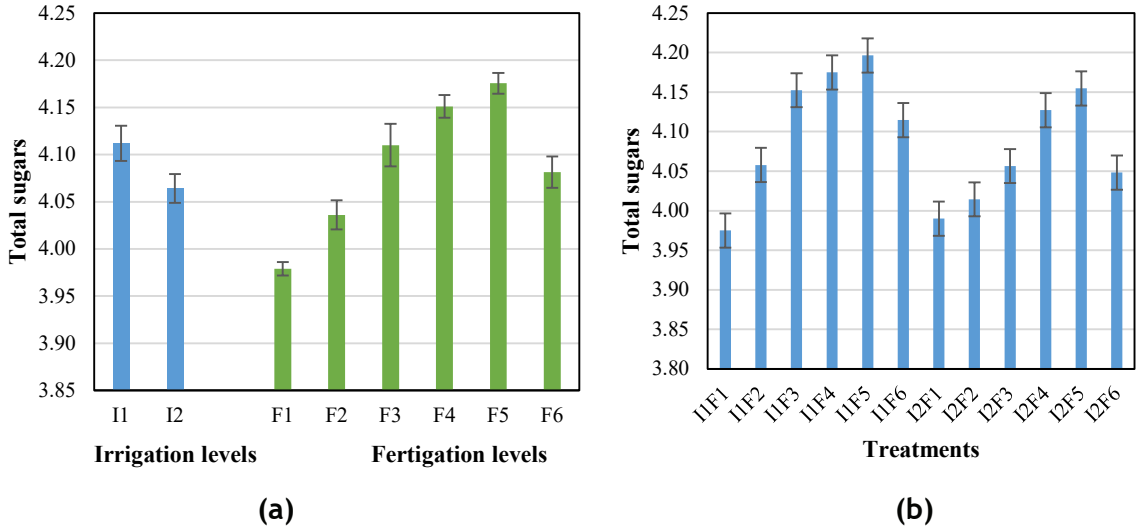


Figure 3. Effect of drip irrigation, fertigation (a) and their interaction (b) on total sugar (%) in tomato.

than I_2 (5.67 °Brix), indicating better accumulation of soluble solids under the I_1 regime. Among fertigation levels, F_5 recorded the highest mean TSS (6.12 °Brix), followed by F_4 (6.06 °Brix) and F_3 (5.90 °Brix), while the lowest value was observed under F_1 (5.24 °Brix). The results clearly demonstrate that higher or balanced fertigation levels enhanced soluble solid accumulation in tomato fruits. The interaction effect I ×F was also significant. The highest TSS value (6.20 °Brix) was recorded under the combination of I_1 with F_5, which was statistically at par with I_1F_4 (6.15 °Brix). In contrast, the lowest TSS (5.18 °Brix) was observed under I_2F_1.

A similar trend was observed for lycopene content (Figure 2). Irrigation level I_1 resulted in significantly higher lycopene content (14.00 mg/100g) compared to I_2 (13.69 mg/100g). Among fertigation treatments, F_5 recorded the highest lycopene content (14.35 mg/100g), which was statistically at par with F_4 (14.23 mg/100g), F_6 (14.17 mg/100g) and F_3 (14.05 mg/100g). The lowest lycopene content was observed under F_1 (12.77 mg/100g). Among interaction, the highest lycopene was recorded under I_1F_5 (14.47 mg/100g), which was statistically at par with I_1F_4 (14.27 mg/100g), I_2F_5 (14.22 mg/100g), I_1F_6 (14.19 mg/100g), I_2F_4 (14.19 mg/100g), I_2F_6 (14.15 mg/100g) and I_1F_3 (14.08 mg/100g) whereas the lowest lycopene content was recorded under I_2F_1 (12.50 mg/100g).

The data pertaining to total sugar also showed a significant variation due to irrigation and fertigation treatments (Figure 3). Among irrigation levels, I_1 recorded the highest total sugar content (4.11 %) compared to I_2 (4.06 %). However, among fertigation treatments, F_5 recorded the maximum total sugar content (4.18 %), which was statistically at par with F_4 (4.15%). The lowest sugar content was observed under F_1 (3.98 %), followed by F_2 (4.05 %). The interaction between irrigation and fertigation was also significant; the highest total sugar content (4.20%) was recorded under the combination of I_1 with F_5, which was statistically at par with I_1F_4 (4.17 %), whereas the lowest total sugar (3.98 %) was observed under I_1F_1.

Higher TSS, lycopene and total sugar under the lower irrigation regime may be attributed to dilution effect and mild moisture stress, which enhances the concentration and redistribution of photosynthates toward fruits, resulting in increased sugar accumulation[12].

Soil Moisture Content (SMC)

Soil Moisture Content (SMC) was significantly affected by irrigation level, depth, crop stage and sampling location (Figure 4). Across all growth stages, irrigation schedule I_2 consistently recorded higher SMC than I_1, indicating improved water availability in the root zone. Moisture was always greater at the dripper location than between drippers, confirming the localised wetting pattern of drip irrigation. Depth-wise, maximum SMC under the dripper was observed at 22.5 cm, whereas between drippers it was highest at 15 cm, with a gradual decline toward 30 cm depth. SMC increased from 30 to 90 DAT and slightly decreased at harvest. The higher moisture in the 15-22.5 cm layer suggests effective water retention within the active root zone with minimal deep percolation losses under I_2 compared to I_1. Similar results were reported by Jaswal *et al.*[6].

Relative Leaf Water Content (RLWC)

All the growth stages (30, 60, 90 DAT and final harvest) showed a distinct and steady trend (Table 3). RLWC values were consistently higher under irrigation level I_2 than under I_1, suggesting that the higher irrigation regime improved plant water status maintenance.

Under both irrigation levels, RLWC gradually increased from 30 DAT to 90 DAT during the crop growth stages before stabilising or slightly declining at the final harvest. The highest mean RLWC was often observed at 90 DAT, indicating superior moisture retention and canopy development during mid-crop growth. With respect to fertigation schedules, no distinct or consistent increasing or decreasing trend was observed. Although numerically F_3, F_4, F_5 and F_6 showed slightly higher RLWC compared to F_1 and F_2 at certain stages, the differences were marginal and

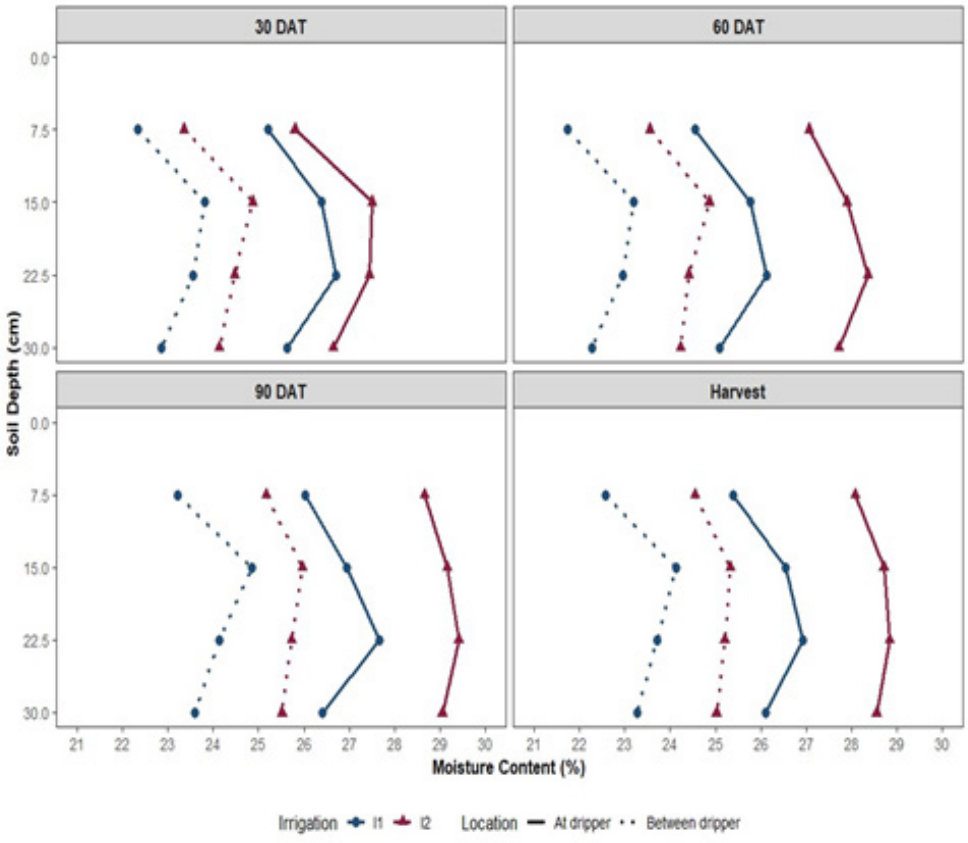


Figure 4. Moisture distribution pattern in soil profile under I_1 and I_2 irrigation treatments in tomato during 2024.

Table 3. Effect of irrigation and fertigation schedules on relative leaf water content (RLWC) in tomato during 2024

Fertigation schedules	RLWC (07:00 AM)											
	30 DAT			60 DAT			90 DAT			Final harvest		
	Irrigation schedules											
	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean
F_1	83.46	84.69	84.08	84.62	85.99	85.31	84.92	86.24	85.58	84.68	85.91	85.30
F_2	83.50	84.71	84.10	84.63	85.95	85.29	84.93	86.26	85.59	84.72	85.93	85.33
F_3	83.62	84.75	84.19	84.78	85.99	85.39	85.03	86.28	85.66	84.75	85.82	85.28
F_4	83.54	84.70	84.12	84.73	85.94	85.34	84.94	86.24	85.59	84.87	85.94	85.41
F_5	83.51	84.73	84.12	84.71	85.97	85.34	84.93	86.32	85.63	84.72	86.02	85.37
F_6	83.53	84.75	84.14	84.69	86.08	85.39	84.96	86.28	85.62	84.76	85.98	85.37
Mean	83.53	84.72		84.70	85.99		84.95	86.27		84.75	85.93	
Factors	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)
I	0.048	0.023	0.016	0.046	0.022	0.016	0.036	0.017	0.012	0.070	0.034	0.024
F	NS	0.040	0.028	NS	0.039	0.027	NS	0.030	0.021	NS	0.058	0.041
I×F	NS	0.057	0.040	NS	0.055	0.039	NS	0.042	0.030	NS	0.082	0.058
Fertigation schedules	**RLWC (13:00 PM)**											
	30 DAT			60 DAT			90 DAT			Final harvest		
	Irrigation schedules											
	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean	I_1	I_2	Mean
F_1	81.19	82.44	81.81	81.80	83.17	82.49	82.16	83.47	82.82	81.92	83.23	82.56
F_2	81.24	82.40	81.82	81.81	83.13	82.47	82.16	83.49	82.82	81.92	83.25	82.58
F_3	81.28	82.48	81.88	81.96	83.17	82.57	82.30	83.53	82.91	82.06	83.29	82.67
F_4	81.23	82.45	81.84	81.91	83.12	82.52	82.24	83.47	82.85	82.00	83.23	82.61
F_5	81.39	82.42	81.90	81.89	83.15	82.52	82.21	83.49	82.85	81.97	83.25	82.61
F_6	81.40	82.49	81.94	81.87	83.26	82.57	82.22	83.57	82.90	81.98	83.33	82.66
Mean	81.29	82.45		81.88	83.17		82.21	83.50		81.97	83.26	
Factors	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)	$CD_{(0.05)}$	SE(d)	SE(m)
I	0.062	0.030	0.021	0.049	0.024	0.017	0.050	0.024	0.017	0.050	0.024	0.017
F	NS	0.052	0.037	NS	0.041	0.029	NS	0.041	0.029	NS	0.042	0.029
I×F	NS	0.073	0.052	NS	0.058	0.041	NS	0.058	0.041	NS	0.059	0.042

where, I1- 0.6 ETc for the first two months and 0.8 ETc thereafter; I2- 0.8 ETc for the first two months and 1.0 ETc thereafter; F1- 25%N+100%PK basal and 75%N fertigation; F2- 25%NK+100%P basal and 75%NKfertigation; F3- 25%NPK basal and 75%NPK fertigation; F4- 50%NPK basal and 50%NPK fertigation; F5- 25%NK+50%P basal and 75%NK+50%P fertigation; F6- 50%NK+75%P basal and 50%NK+25%P fertigation

statistically non-significant. This indicates that leaf water status was largely influenced by irrigation rather than nutrient scheduling.

Higher RLWC observed under irrigation level I_2 indicates better plant water status due to optimum soil moisture availability, which helps in maintaining cellular turgidity and physiological activity[6]. The progressive increase in RLWC up to 90 DAT reflects enhanced canopy development and root establishment during active growth stages. Lower afternoon RLWC compared to morning values confirms the effect of higher evaporative demand and transpiration losses during midday hours. The non-significant effect of fertigation schedules suggests that leaf water status was predominantly governed by irrigation level rather than nutrient application under protected conditions. Similar results were reported by Patanè *et al.*[4] and Mukherjee *et al.*[19].

CONCLUSIONS

The present investigation demonstrated that irrigation and fertigation management significantly influenced plant water relations, growth, yield and fruit quality. Irrigation at 0.8 ET_c for the first two months and 1.0 ET_c thereafter (I_2) maintained better plant water status, resulting in earlier flowering and harvesting as well as improved yield attributes. Among the fertigation schedules, application of 25% NK along with 50% P as basal, supplemented with fertigation of the remaining 75% NK and 50% P (F_5), was found to be the most effective due to the balanced and stage-wise supply of nutrients, which enhanced fruit number, fruit weight and overall productivity. In contrast, irrigation at 0.6 ET_c for the first two months and 0.8 ET_c thereafter (I_1) slightly improved quality parameters such as total soluble solids, lycopene content and total sugars, possibly due to mild moisture stress that increased assimilate concentration in fruits. Overall, the combined application of higher irrigation (I_2) with the optimised fertigation schedule (F_5) proved most suitable for achieving higher productivity while maintaining desirable fruit quality under protected cultivation.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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AUTHORS CONTRIBUTION

P: conducted the experiment, analyzed the data and wrote the original manuscript. SKS: conceptualize the research programme, methodology, provided resources, reviewed and edited the manuscript.