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RESEARCH ARTICLE

Effect of fertigation scheduling and doses of NPK on growth, yield and quality of cherry tomato (*Solanum lycopersicum L. var. cerasiforme*) under protected condition

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Abstract

This study investigated the impact of different fertigation schedules on cherry tomato (*Solanum lycopersicum* var. *cerasiforme*) cultivation in a controlled environment at TNAU, Coimbatore, India. A Completely Randomized Design with nine treatments and three replications was used, incorporating various combinations of soil application and fertigation with water-soluble fertilizers at 25%, 50%, 75%, and 100% of the recommended dose of fertilizer (RDF). Critical parameters such as growth, phenological traits, yield, fruit quality, soil nutrient status, and plant nutrient uptake were evaluated. Statistical analyses, including ANOVA, path coefficient analysis, and principal component analysis (PCA), were performed to assess treatment effects and identify relationships between variables. The results consistently demonstrated that fertigation with water-soluble fertilizers at 100% RDF (T_3) yielded the best outcomes for most parameters, followed by 75% RDF fertigation (T_4) and a combination of 25% soil application and 75% fertigation (T_7). Significant improvements in plant growth, yield and fruit quality were observed with optimized fertigation compared to traditional soil application methods. T_3 (100% RDF through fertigation) resulted in the highest plant height (263.95 cm), number of primary branches (15), leaf area (316.77 cm^2) and dry matter production (96.85 kg/plant). Yield attributes such as fruits per plant (326.50), fruit weight (3.73 g), and total yield (23.95 t/ha) were also highest in T_3. Path coefficient analysis indicated strong positive correlations between growth and yield parameters. PCA showed that the first principal component accounted for 85.9 % of the total variation. These findings highlight the potential for fertigation to improve resource use efficiency and productivity in cherry tomato cultivation.

Keywords

cherry tomato; drip irrigation; fertigation; nutrient uptake; water-soluble fertilizer

Introduction

Tomatoes hold significant economic and social value in Brazil and are grown in many regions nationwide (1). However, a substantial challenge in tomato cultivation is producing high-quality fruits with a high yield (2). The

cherry tomato, often considered an exotic vegetable, adds a unique flavour and appearance to dishes and appetizers. Cherry tomatoes are known for their small size, typically weighing 15-25 grams. They are bright red, resembling a cherry and possess excellent taste.

Protected cultivation, or Controlled Environment Agriculture (CEA), is a farming technique where the micro-climate is controlled to influence plant growth and development (3). Essential factors like temperature, humidity and light are regulated according to the crop's needs. Common protected cultivation structures used by Indian farmers include greenhouses, polyhouses, shade net houses, and low tunnels (4). A polyhouse is a framed structure made of transparent or translucent low-density polyethene, UV-stabilized to a thickness of 200 microns (800 gauges). This polyethylene creates a greenhouse effect, providing an ideal microclimate for plant growth and development (5). A protected environment enhances crop yield, improves product quality and reduces water consumption (6).

Water use is optimized, and consumption is reduced by 40-50% (7). Frequent application of small quantities of water directly above and below the soil surface, typically as discrete drops, continuous drips, tiny streams, or micro sprays, delivered through emitters or applicators placed along a water delivery line. This method irrigates and fertilizes the plant rather than the soil. Fertigation allows nutrients to be applied directly to the area with the highest concentration of active roots and according to the crop's needs (8). By scheduling fertilizer applications based on necessity, nutrient losses associated with conventional methods can be minimized, increasing nutrient use efficiency. Fertigation can save between 25-50 % on fertilizers (9).

Additionally, applying fertilizers and pesticides through a drip irrigation system enhances efficiency, saves labour, and offers greater flexibility in scheduling applications to meet crop requirements (10). Fertigation enhances fertilizer use efficiency by 40-60%. Hence, the recommended doses of fertilizers may be reduced proportionally. Drip irrigation promotes root growth in the surface layer (about 70-80%); therefore, the nutrients from sub-surface layers may not be extracted. (11, 12). Applying recommended fertilizer doses provides plants with the necessary nutrients for optimal growth and higher yields. It helps avoid both nutrient deficiencies and excesses, ensuring healthy plant development.

Correct fertilization practices also minimize environmental pollution from overuse. In the long run, it supports sustainable agriculture by preserving soil health and productivity. This study hypothesises that optimizing fertigation schedules for cherry tomatoes cultivated in a protected environment will enhance growth, yield and fruit quality by aligning nutrient and water supply with the plants' developmental needs. This research is essential as fertigation allows for efficient use of resources, reducing water and nutrient wastage while improving crop performance. In a controlled environment, factors like temperature and humidity can be regulated, allowing for the isolation of fertigation effects.

Additionally, fertigation helps mitigate soil-related issues such as salinity and nutrient leaching, promoting sustainable, climate-resilient agriculture for high-value crops like cherry tomatoes. The prospects of this study include developing precision fertigation protocols that improve water and nutrient efficiency. It could promote sustainable agriculture by minimizing environmental impacts like nutrient leaching. The approach may also enhance climate resilience in agriculture in a controlled environment. Integrating advanced technologies could also optimise fertility for consistent crop yield and quality.

Materials and Methods

Location and Soil of Experimental Site

The experiment was conducted at the naturally ventilated shade net house (50%) in the Orchard of Vegetable Science department, Horticulture College and Research Institute, TNAU, Coimbatore. 76.9326 ° E longitude and 11.0152° N latitude at 427m above mean sea level. The soil is classified as black soil. The size of the polyhouse was 28 × 32 m (896 m^2), covered with an aluminate sheet and ultraviolet-stabilized low-density polyethylene sheet 200 microns thick with the provision of a fogger installed overhead. The soil pH was 8.12, with an electrical conductivity of 0.91 dsm^{-1}, organic carbon content of 0.38%, soil bulk density of 1.11gcm-3 and moisture content of 2.56 % from 2023-2024. It has low available nitrogen (232.0 kg ha^{-1}), medium phosphorus (18.4kg ha^{-1}), and high potassium (429.0 kg ha^{-1}).

Experimental Treatments

The experiment was laid out in a Completely Randomized Design with three replications. There were nine treatments viz., T_1: Control (without fertilizer application), T_2: Control (Soil application with straight fertilizer at 100% RDF), T_3: Fertigation with water-soluble fertilizers at 100% RDF, T_4: Fertigation with water-soluble fertilizers at 75% RDF, T_5: Fertigation with water-soluble fertilizers at 50% RDF, T_6: Fertigation with water-soluble fertilizers at 25% RDF, T_7: Soil application with straight fertilizer at 25% + Fertigation with water-soluble fertilizers at 75% RDF, T_8: Soil application with straight fertilizer at 50% + Fertigation with water-soluble fertilizers at 50% RDF, T_9: Soil application with straight fertilizer at 75% + Fertigation with water-soluble fertilizers at 25% RDF. Cherry tomato (Pusa cherry tomato-1) seeds were sown in plastic pro-trays with 1.5-inch cells containing a growth medium composed of coco peat, vermiculite and perlite in a 2:1:1 ratio. Raised beds were prepared 30 cm above ground level, with a width of 1 meter, following the length of the polyhouse. A spacing of 60 cm between rows and 60 cm between plants was maintained. Standard agricultural practices were followed throughout the investigation. Pest and disease control measures were applied as needed during the growing season. Plants were vertically trained using plastic twine. A comprehensive range of growth parameters (such as plant height at flowering, plant height at final harvest, days to first flowering, number of flowers per cluster, number of

flowering clusters, number of fruits per cluster, number of fruit clusters per plant, days from fruit set to fruit maturity, and percentage of fruit set), fruit and yield metrics (including number of fruit per plant, fruit length, fruit girth, number of locules per fruit, fruit weight, yield per plant, and yield per hectare).

Physiological Parameters

SPAD value

For each treatment and replication, the SPAD (Soil Plant Analysis Development) values were measured in the leaves of five labelled plants at harvesting time. This measurement was taken by manually attaching a SPAD chlorophyll meter to the leaf tissue on the day of harvesting.

Dry matter production (kg/ha)

Randomly selected terminal head parts were taken from five plants in each treatment group. Chopping of these samples commenced after their weights were recorded. The samples were then oven-dried at 60°C until a consistent weight was achieved. After drying, the samples were weighed again and the dry matter content was calculated as a percentage.

Nutrient Uptake by Plants (kg/ha)

The micro-Kjeldhal method determined nitrogen content (%) (13). Phosphorus content (%) was estimated using the Vanadomolybdate yellow colour method as reported (14). Potassium content (%) was assessed using a flame photometer in the triacid digest (15). The nitrogen, phosphorus and potassium uptake levels were calculated below and the contents were presented as kg/ha.

$$\text{N uptake (kg/ha)} = \frac{\text{N content (\%)} \times \text{Dry matter production (kg/ha)}}{100}$$

$$\text{P uptake (kg/ha)} = \frac{\text{P content (\%)} \times \text{Dry matter production (kg/ha)}}{100}$$

$$\text{K uptake (kg/ha)} = \frac{\text{K content (\%)} \times \text{Dry matter production (kg/ha)}}{100}$$

Biochemical Parameters

Total Soluble Solids (Deg Brix)

The total soluble solid content of the fruit pulp was measured using a Zeiss hand refractometer and expressed in ⁰Brix.

Total sugars (mg/100g)

The total sugars were estimated using the protocol outlined for carbohydrate analysis (16). A 250 mg fruit sample was macerated in 10 ml of 80% ethanol centrifuged and 0.5 ml of the supernatant was evaporated at 50°C. The residue was dissolved in 5 ml of distilled water. Then, 0.5 ml of this solution was mixed with 1 ml of distilled water and 4 ml of Anthrone reagent, heated in a boiling water bath for 8 minutes and cooled. The absorbance was measured at 630 nm using a UV-VIS spectrophotometer. The sugar content was calculated using a glucose standard graph and expressed in mg per 100 g.

Ascorbic acid (mg/100g)

Ascorbic acid content was measured as per the protocol outlined by the Association of Official Analytical Chemists (17). A 5 g fruit pulp sample was mixed with 50 ml of 4% oxalic acid, filtered and titrated against 2,6-dichlorophenol indophenol dye until a light pink colour persisted for 5 seconds. The ascorbic acid content was calculated using the formula:

$$\text{Ascorbic acid (mg/100g)} = \frac{\text{(Titrate value} \times \text{Dye factor} \times \text{Volume made up)}}{\text{(Aliquot taken} \times \text{Sample weight)}} \times 100$$

The dye factor was determined by titrating a standard ascorbic acid solution.

Titrable Acidity (%)

Titrable acidity was measured per the protocol outlined by the Association of Official Analytical Chemists (16). 5g of cherry tomato pulp was mixed with 50 ml of hot distilled water, filtered and the filtrate was titrated with 0.1N NaOH using phenolphthalein as an indicator. The endpoint was a stable pale pink colour. The titrable acidity was calculated using the formula:

$$\text{Titrable acidity (\%)} = \frac{\text{Titer value x Normality} \times \text{m. eq. Weight of acid}}{\text{Volume of sample}} \times 100$$

Lycopene Content (mg/100g)

Lycopene content was determined following the standard procedure for analysing fruits and vegetables and is expressed in mg/100g (18). One gram of fruit pulp was extracted with acetone until the residue was colourless. The extract was mixed with petroleum ether in a separating funnel and 5% sodium sulphate was added to separate phases. The process was repeated until the lower phase became colourless. Anhydrous sodium sulphate was added to the pooled petroleum ether extract and filtered in darkness for 20 minutes. The volume was adjusted to 100 ml. A 5 ml aliquot was diluted to 25 ml and absorbance was measured at 503 nm. Lycopene content was calculated using the formula:

$$\text{Lycopene content (mg/100g)} = \frac{3.1206 \times \text{Absorbance of sample at 503 nm} \times \text{total volume}}{\text{Weight of the sample} \times 1000} \times 100$$

Beta carotenoid content (mg/100g)

Beta-carotene content was estimated following the standard procedure for analysing fruits and vegetables and is expressed in mg/100g (19). One gram of pulp was extracted with acetone until the residue was colourless. The extract was mixed with petroleum ether and 5% sodium sulphate in a separating funnel. The upper petroleum ether layer was removed and the aqueous phase was re-extracted with petroleum ether. The pooled extract was treated with anhydrous sodium sulphate for 20 minutes, then filtered, and the volume was made up to 25 ml with petroleum ether. Absorbance was measured at 453 nm. Beta-carotene content was calculated using the formula:

$$\text{Beta carotene (mg/100g)} = \frac{\text{The absorbance of sample} \times \text{Total volume x 100}}{0.2592 \times \text{Weight of the sample (g)} \times 1000} \times 100$$

Five plants were randomly selected from each replication for data analysis, and the mean data was used. ANOVA was performed to assess the significance of differences between treatments, using KAU Grapes software for agricultural data processing and R version 4.4.1 for further analysis. This approach ensures the results reflect overall trends and provide reliable insights into treatment effects.

Results

Analysis of Variance (ANOVA)

Effect of Fertigation on Growth and Yield

The response of various growth and yield parameters in cherry tomatoes to different levels of N, P, and K fertigation schedules is detailed in Table 1. Growth parameters such as plant height, number of primary branches, internodal length, stem diameter, days to first flowering, number of flower clusters per plant, number of fruit clusters per plant, days from fruit set to maturity, fruit set percentage, number of fruits per plant, fruit length, fruit girth, number of locules per fruit, fruit weight, yield per plant and yield per hectare were significantly higher in the treatment that applied water-soluble fertilizers through fertigation at 100% RDF (T_3), followed by fertigation with water-soluble fertilizers at 75% RDF (T_4) and soil application with straight fertilizer at 25% + fertigation with water-soluble fertilizers at 75% RDF (T_7). The highest average plant height was observed in treatment T_3, reaching 189.59 cm, followed by T_4. Additionally, the average number of primary branches (15), internodal length (3.69 cm) and stem girth (3.71cm) exhibited the greatest performance in the 100% RDF treatment (T_3), followed by T_4. (Fig. 1a, 1b, 1c, 1d). T_3 blooming occurs more quickly than other treatments (26.41 days), followed by T_4 and T_7 (Fig 1e). T_3 had the greatest number of flowers in the cluster (51.64), followed by T_4 (Fig 1F). The highest number of fruits per cluster was found with water-soluble fertilizers by fertigation at 100% RDF (T_3) (17.33), followed by T_4 (Fig 1g). The least number of days from flowering to maturity (21.16 days) was noted in T_3, followed by T_4 and T_7. T_3 (34.72%) had the greatest impact on the percentage of fruit set, followed by T_4. (Fig. 1H, 1I). T_3 obtained the maximum number of fruits per plant (326.50), followed by T_4 and T_7 (Fig. 1J). T_3 had a significant effect on fruit length (2.97 cm), circumference (5.15 cm) and width (0.98 cm) (Fig. 1k, 1l, 1m). T_3 was shown to be the treatment with the highest individual fruit weight (3.73g), yield per plant (1211.38 g/plant) and yield per hectare (23.95 t/ha), followed by T_4 and T_7 (Fig. 1n, 1o, 1p).

Effect of Fertigation on Physiological Parameters

In cherry tomatoes, the reaction of varied amounts of N, P, and K fertigation regimens on various physiological and quality indicators is detailed in Table 2. Physiological parameters such as leaf area, leaf area index, soil available nutrients N, P, K, nutrient uptake N, P, K at the final harvesting stage, total chlorophyll at 60 and 90 DAT and dry matter production were all parameters highest in treatment with that applied water-soluble fertilizers through fertigation at 100% RDF (T_3), followed by fertigation with water-soluble fertilizers at 75% RDF (T_4) and soil application with straight fertilizer at 25% + Fertigation with water-soluble fertilizers at 75% RDF (T_7). T_3 had the highest leaf area (309.58cm^2) and leaf area index (LAI) (0.859), followed by T_4 and T_7 among all the treatments (Fig. 2a, 2b). When comparing treatments T_3, T_4, and T_7, the availability of nutrients in the soil and the efficiency of nutrient absorption during the final stages of harvesting played a critical role. Treatment T_3 (Drip fertigation at 100% RDF) had the maximum nitrogen, phosphorus, and potassium uptake of 135.28 kg/ha, 22,71 kg/ha and 173.81 kg/ha which was statistically comparable to treatment T_4 (Drip fertigation at 75% RDF), where nitrogen uptake was 131.99 kg/ha, 20.67 kg/ha, 166.62 kg/ha when compared to all other treatments (Fig. 2c, 2d, 2e). Treatment T_3 (Fertigation at 100% RDF) had the most significant recorded amount of accessible N, P, K (256.31 kg/ha) (20.4 kg/ha) (225.78 kg/ha) in the soil after harvesting. It was comparable to treatment T_4 (Fertigation at 75% RDF) (Fig. 2f, 2g, 2h). T_3 had higher chlorophyll content at 60 DAT (56.7) And 90 DAT (40.83), followed by T_4 and T_7. T_3 had higher dry matter production (96.85 kg/ha), followed by T_4 (94.05) and T_7 (Fig. 2k).

Effect of Fertigation on Quality

Following analysis, significant changes were seen in all treatments. The amount of lycopene in fresh tomato fruit varies depending on the tomato type, fruit maturity, and ambient factors (Table 3). Based on the evaluation of many treatments, the fertigation NPK @ 100% (T_3) exhibited the most significant levels of lycopene content

Table 1: Effects of diverse fertigation treatments on the growth and yield of Cherry Tomato

Treatment	Plant height at final harvest (cm)	Number of primary branches	Internodal length (cm)	Stem girth (cm)	Days for first flowering (days)	Number of flowers per cluster	Number of fruits per cluster	Percentage of fruit set (%)	Number of fruits per plant	Fruit length(cm)	fruit girth (cm)	Single fruit weight (g)	Yield per plant (g/ plant)	Yield ha^{-1} (t/ha)
T_1	243.70^{f}	8.47^{f}	2.01^{f}	2.72^{f}	35.68^{f}	38.03^{e}	8.24^{e}	21.62^{g}	214.70^{b}	2.75	3.53^{d}	3.28^{e}	697.9	13.96^{d}
T_2	246.00^{ef}	8.67^{f}	2.21^{e}	2.80^{ef}	35.35^{ef}	41.72d^{e}	8.31^{e}	24.62f	316.77^{a}	2.79	3.76^{cd}	3.37^{de}	723.9	14.48^{d}
T_3	263.95^{a}	15.00^{a}	3.69^{a}	3.71^{a}	26.41^{a}	51.64^{a}	17.33^{a}	34.72a	326.50^{a}	2.97	5.14^{a}	3.73^{a}	1211.3	23.95^{a}
T_4	261.57^{b}	14.30^{a}	3.19^{b}	3.26^{b}	28.50^{b}	51.04^{a}	17.29^{a}	33.89a	325.38^{a}	2.95	5.06^{a}	3.70^{ab}	1183.5	23.67^{a}
T_5	256.82^{c}	10.40^{cd}	2.69^{c}	2.94^{de}	31.31^{de}	49.37^{ab}	15.27^{b}	30.10bc	323.66^{a}	2.88	4.40^{b}	3.54^{abcd}	1077.6	21.55^{b}
T_6	248.03^{e}	9.33^{ef}	2.26^{de}	2.84^{ef}	34.68^{e}	43.17^{cd}	11.41^{d}	25.81ef	318.17^{a}	2.84	3.77^{cd}	3.40^{de}	929.9	18.54^{c}
T_7	257.62^{c}	12.27^{b}	3.17^{b}	3.21^{bc}	29.89^{c}	50.09^{ab}	17.20^{a}	31.57b	323.72^{a}	2.91	4.97^{a}	3.66^{abc}	1148.0	22.96^{a}
T_8	253.95^{d}	11.00^{c}	2.65^{c}	3.05^{cd}	32.59^{d}	48.83^{ab}	15.23^{b}	29.17cd	319.64^{a}	2.88	4.02^{c}	3.47^{bcde}	1054.0	21.08^{b}
T_9	252.48^{d}	9.87^{de}	2.37^{d}	2.91^{de}	34.47^{de}	46.10^{bc}	13.59^{c}	27.81de	319.28^{a}	2.86	3.80^{cd}	3.46^{cde}	945.3	18.91^{c}
SE (d)	8.42	0.14	0.05	0.04	1.70	2.10	0.71	1.19	15.83	0.13	0.25	0.20	39.5	0.89
CV	4.97	1.94	2.96	2.09	6.49	5.50	6.28	5.06	6.26	5.39	7.07	7.07	5.94	6.66
CD (5%)	17.57	0.30	0.11	0.09	3.60	4.44	1.50	2.53	33.57	0.27	0.52	0.43	82.47	1.85

*Significant at 5% level, CD: critical difference; SE: standard error, CV: Coefficient of Variation.

T_1- Without Fertilizer Application

T_2 - Soil application with straight fertilizer @ 100% RDF

T_3- Fertigation with water-soluble fertilizers @ 100% RDF

T_4 - Fertigation with water-soluble fertilizers @ 75% RDF

T_5 - Fertigation with water-soluble fertilizers @ 50% RDF

T_6- Fertigation with water-soluble fertilizers @ 25% RDF

T_7- Soil application with SF @ 25% + Fertigation with WSF @ 75% RDF

T_8- Soil application with SF @ 50% + Fertigation with WSF @ 50% RDF

T_9- Soil application with SF @ 75% + Fertigation with WSF @ 25% RDF

Table 2: Effects of diverse fertigation treatments on Physiology of cherry tomato

Treatment	Leaf area (cm^2)	Leaf area index	Nitrogen uptake (kg/ha)	Phosphorus Uptake (kg/ha)	Potassium uptake (kg/ha)	Post-harvest available nitrogen in soil (kg/ha)	Post-harvest soil available Phosphorus in soil (kg/ha)	Post-harvest soil - available Potassium in soil (kg/ha)	Total chlorophyll at 60 DAT (SPAD)	Total chlorophyll at 90 DAT (SPAD)	Dry matter production (kg/ha)
T_1	274.64	0.762^{d}	30.28^{e}	5.40^{f}	34.5^{d}	50.65^{d}	6.5^{e}	40.5^{e}	48.07^{d}	35.26	74.5^{f}
T_2	280.43	0.778^{d}	90.26^{cd}	16.18^{e}	150.39^{c}	227.1^{c}	20.4^{d}	225.78^{d}	49.6^{cd}	35.82	77.55^{f}
T_3	309.58	0.859^{a}	135.28^{a}	22.71^{a}	173.81^{a}	256.31^{a}	23.83^{a}	265.98^{a}	56.7^{a}	40.83	96.85^{a}
T_4	302.88	0.841^{ab}	131.99^{a}	20.67^{b}	166.62^{ab}	250.27^{abc}	22.34^{bc}	258.91^{ab}	56.46^{a}	39.85	94.05^{ab}
T_5	291.85	0.810^{abcd}	112.24^{c}	18.93^{c}	152.21^{c}	245.47^{abc}	22.05^{c}	247.56^{bc}	52.28^{bc}	37.7	84.12^{cde}
T_6	286.81	0.796^{bcd}	91.52^{d}	17.38d^{e}	150.42^{c}	230.65^{bc}	21.65^{c}	231.28^{d}	51.27^{bcd}	36.1	78.91^{ef}
T_7	298.33	0.828^{abc}	122.32^{b}	19.40^{bc}	164.43^{b}	254.32^{ab}	23.29^{ab}	262.94^{ab}	54.63^{ab}	39.83	89.54^{abc}
T_8	288.58	0.801^{abcd}	109.3^{c}	18.9^{c}	154.95^{c}	247.65^{abc}	22.08^{c}	257.65^{ab}	51.21^{bcd}	38.12	86.93^{bcd}
T_9	276.59	0.768^{d}	94.52^{d}	17.35^{de}	150.98^{c}	234.13^{abc}	21.45^{cd}	237.6^{cd}	50.54^{bcd}	36.52	81.82^{def}
SE (d)	14.09	0.03	3.59	0.68	6.19	9.51	0.68	7.64	0.60	0.64	2.91
CV	7.27	5.29	5.27	5.87	6.42	6.42	5.03	5.07	1.72	2.53	5.13
Cd (5%)	29.38	0.06	7.49	1.43	12.9	19.85	1.43	15.93	1.25	1.33	6.07

*Significant at 5% level, CD: critical difference; SE: standard error, CV: Coefficient of Variation.

T_1- Without Fertilizer Application

T_2 - Soil application with straight fertilizer @ 100% RDF

T_3- Fertigation with water-soluble fertilizers @ 100% RDF

T_4 - Fertigation with water-soluble fertilizers @ 75% RDF

T_5 - Fertigation with water-soluble fertilizers @ 50% RDF

T_6- Fertigation with water-soluble fertilizers @ 25% RDF

T_7- Soil application with SF @ 25% + Fertigation with WSF @ 75% RDF

T_8- Soil application with SF @ 50% + Fertigation with WSF @ 50% RDF

T_9- Soil application with SF @ 75% + Fertigation with WSF @ 25% RDF

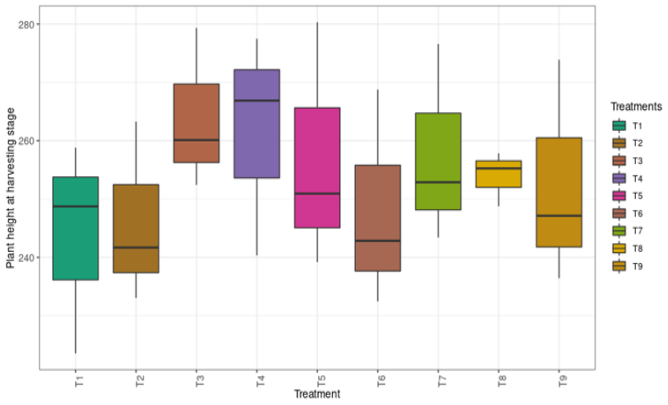


Fig. 1a

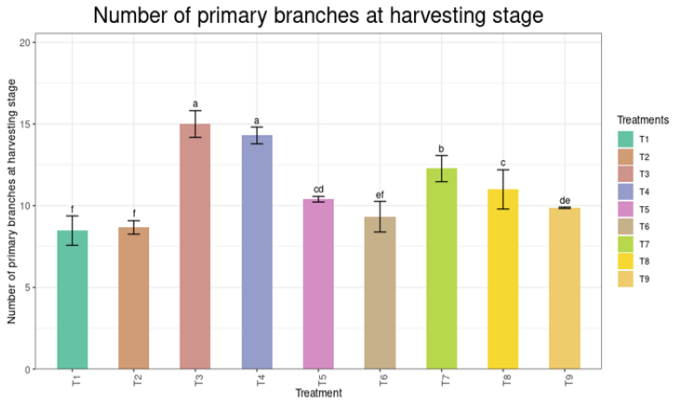


Fig. 1b

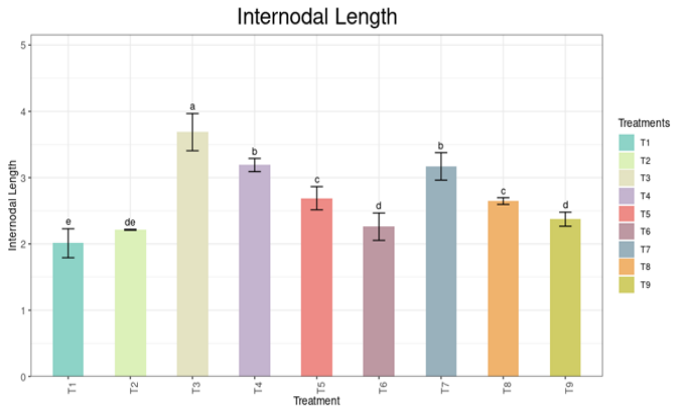


Fig. 1c

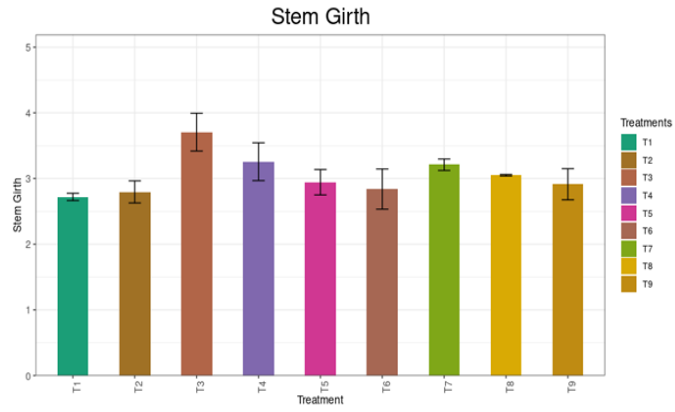


Fig. 1d

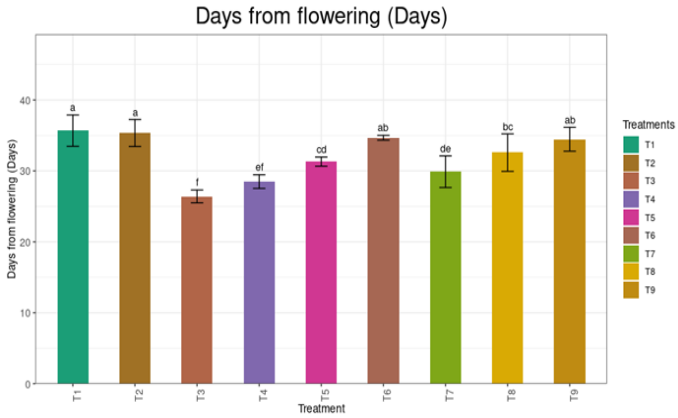
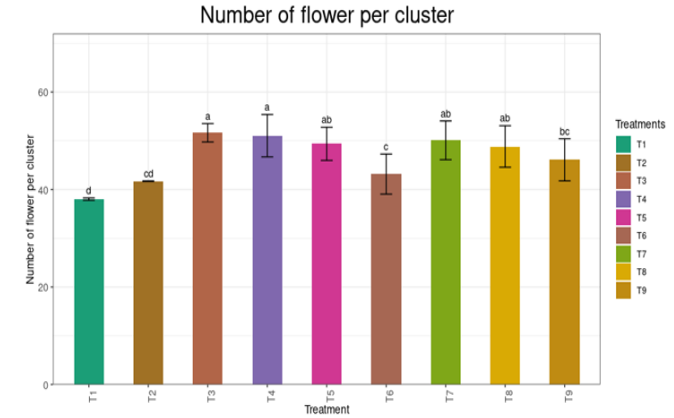


Fig. 1e



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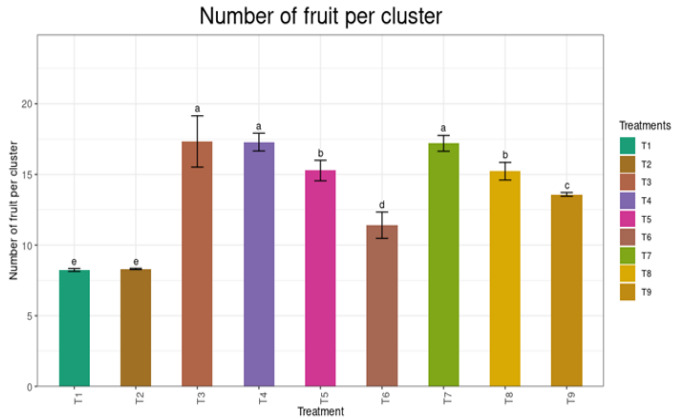


Fig. 1g

Fig. 1h

Fig.1 Graphical representation compares productivity-enhancing traits including plant height at the harvesting stage (1a), number of primary branches at the harvesting stage (1b), Inernodal length (1c), Stem girth (1d), Days to flowering (1e), Number of flowers per cluster (1f), number of fruit per cluster (1g), Fruit setting percentage (1h), Days to flowering to fruiting (1i), number of fruit per plant (1j), Fruit length (1k), Fruit girth (1l), Individual fruit weight (1m), Yield per plant (1n), Yield per hectare (1o).

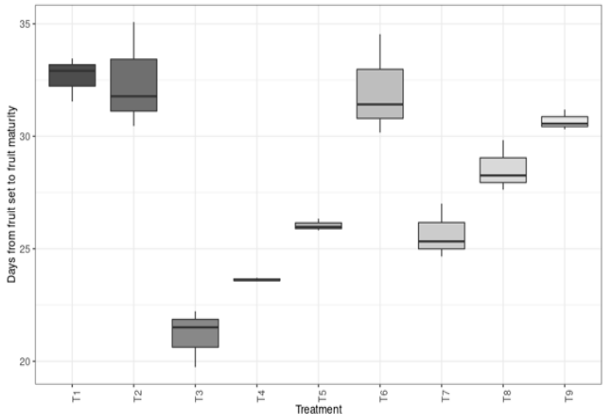
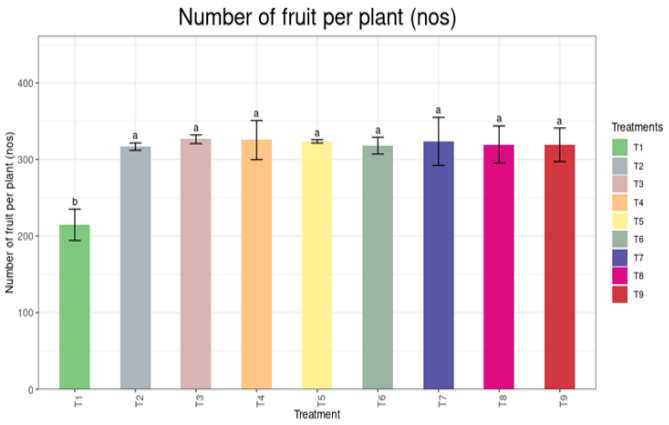


Fig. 1i



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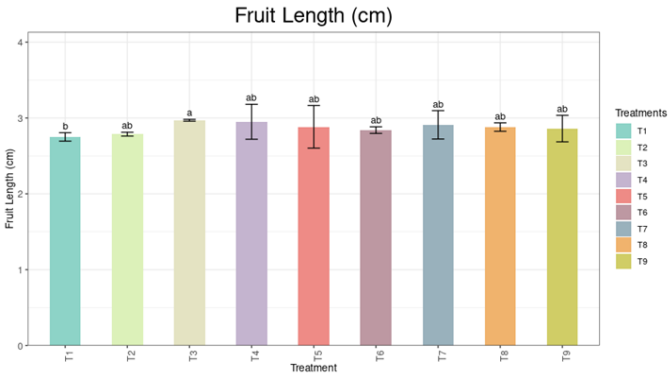

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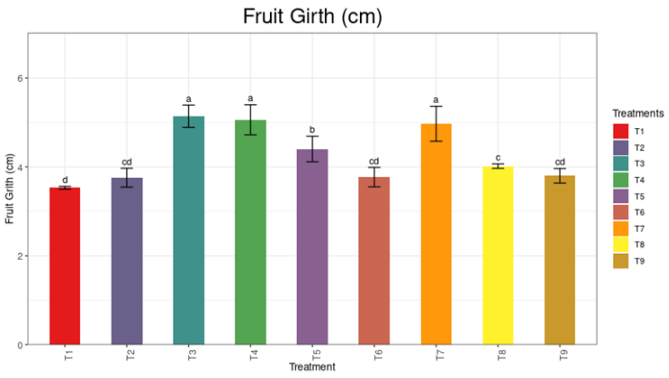
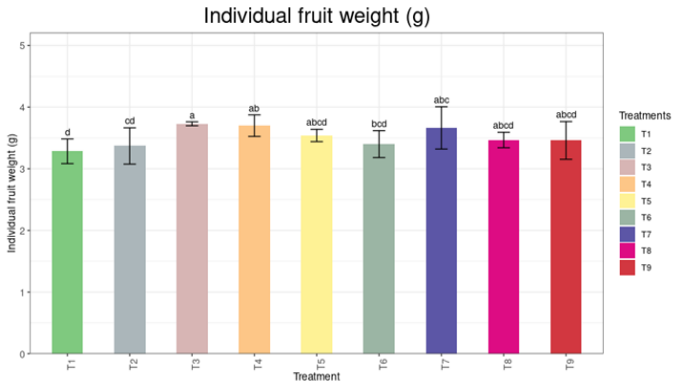


Fig. 1l



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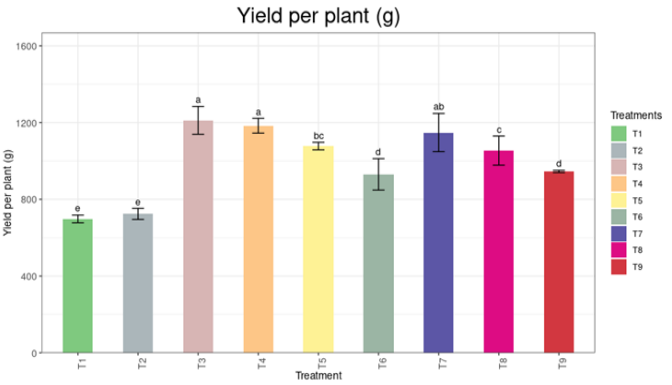


Fig. 1n

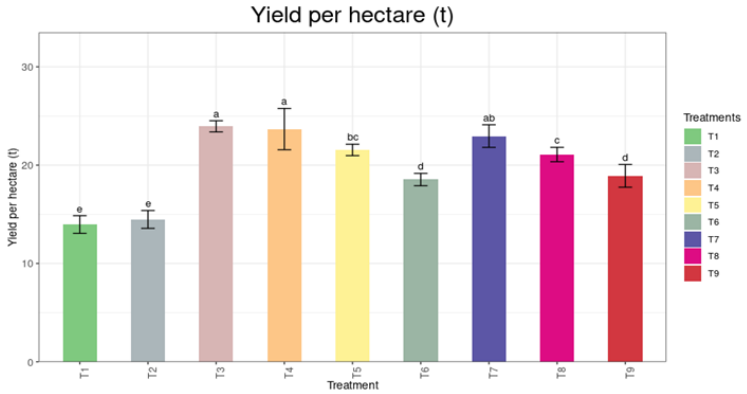


Fig. 1o

Fig.1 Graphical representation compares productivity-enhancing traits including plant height at the harvesting stage (1a), number of primary branches at the harvesting stage (1b), Inernodal length (1c), Stem girth (1d), Days to flowering (1e), Number of flowers per cluster (1f), number of fruit per cluster (1g), Fruit setting percentage (1h), Days to flowering to fruiting (1i), number of fruit per plant (1j), Fruit length (1k), Fruit girth (1l), Individual fruit weight (1m), Yield per plant (1n), Yield per hectare (1o).

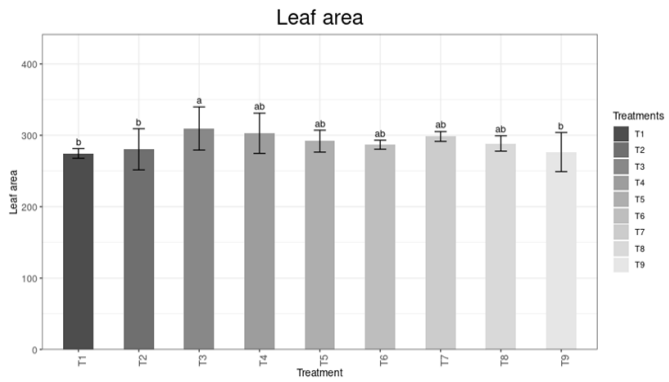


Fig. 2a

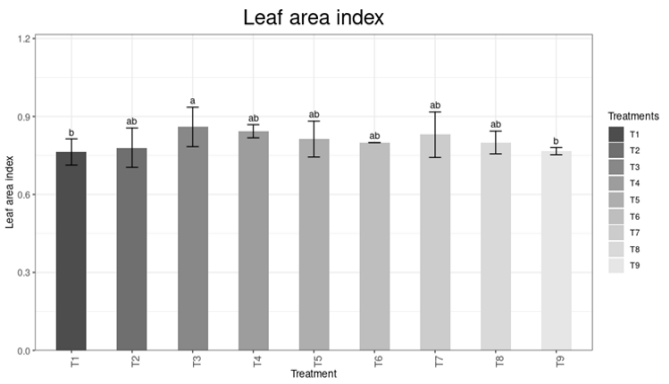


Fig. 2b

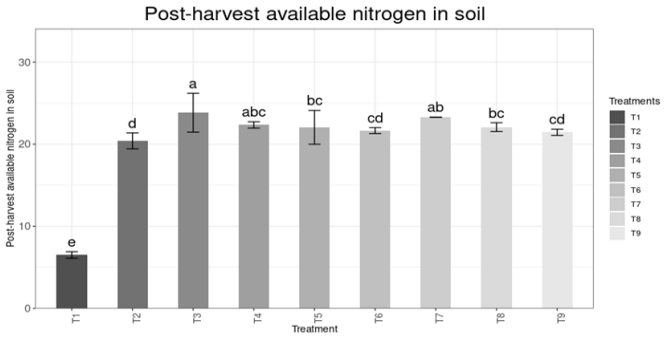


Fig. 2c

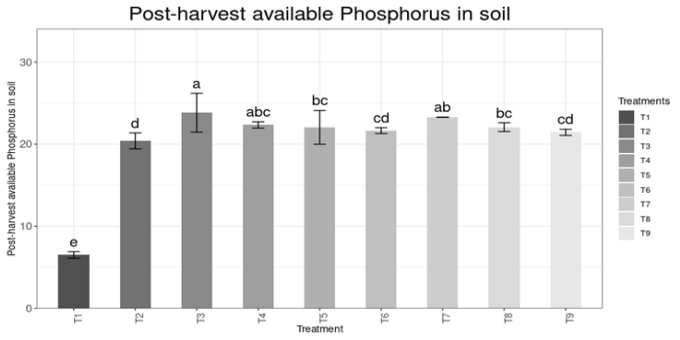


Fig. 2d

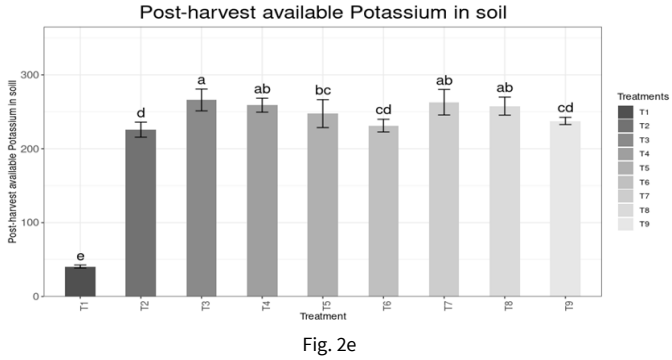
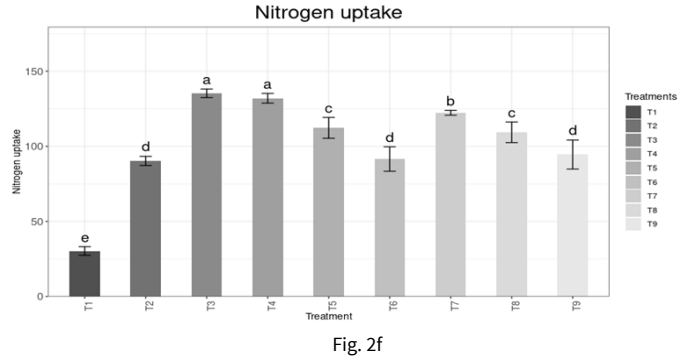


Fig. 2e



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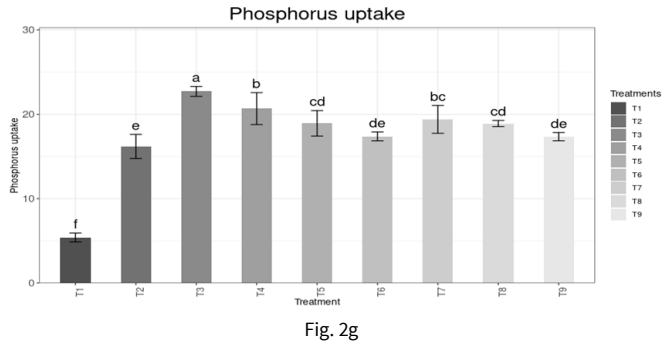

Fig. 2g

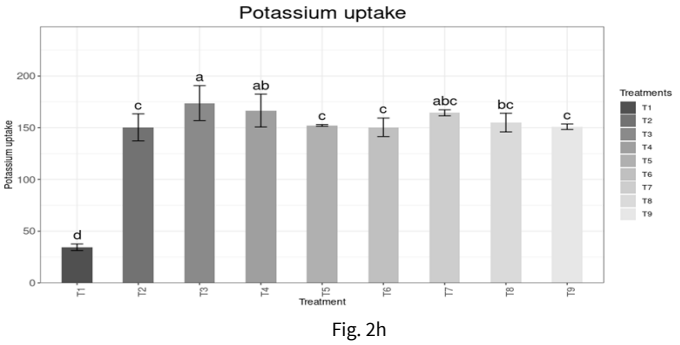

Fig. 2h

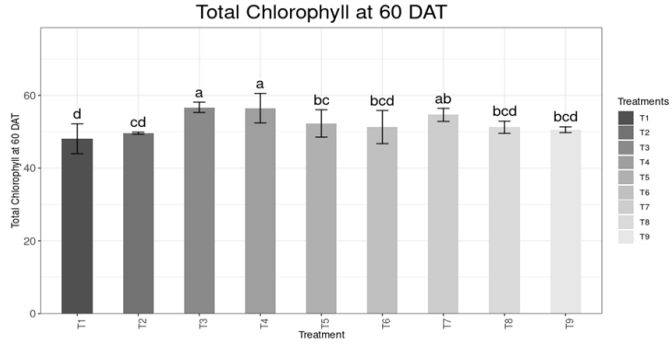

Fig. 2i

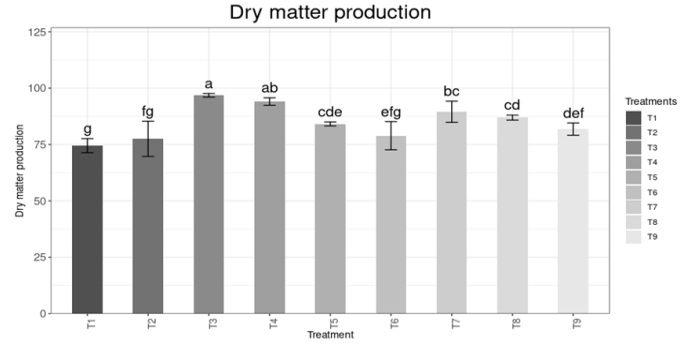

Fig. 2j

Fig. 2 Graphical representation compares productivity-enhancing traits including leaf area (2a), leaf area index (2b), Post-harvest soil available nitrogen (2c), Post-harvest soil available phosphorus (2d), Post-harvest soil available potassium (2e), Nitrogen uptake (2f), Phosphorus uptake (2g), potassium uptake (2h), Chlorophyll at 60 DAT (2i), Dry matter production (2j).

(8.16 mg $100g^{-1}$), ascorbic acid (27.87 mg $100g^{-1}$) and total soluble solids (6.01^0Brix), total sugar (2.04 mg $100g^{-1}$), total carotene (11.45 mg $100g^{-1}$), Titrable acidity (0.96 mg $100g^{-1}$) and fruit locule (2.02), followed by T_4 and T_7 when compared all other treatments (Fig. 3a, 3b, 3c, 3d, 3e, 3f, 3g). The lowest level of quality, such as lycopene, ascorbic acid, TSS, total sugar, total carotene, titrable acidity and fruit locule, was seen in T_1 and T_2 (fertilizer application done conventionally and without fertilizer). There was no discernible difference in fruit firmness and Shelf life across the treatment (Table 3).

Path Analysis

The path coefficient analysis of cherry tomato growth and yield attributes reveals that several traits have significant direct and indirect effects on yield per plant. The number of flowers per cluster shows the highest positive direct effect on yield (0.613), followed by soil-available phosphorus (0.459) and yield per plant itself (0.388). Other essential traits include lycopene content (0.356), nitrogen uptake (0.315) and ascorbic acid (0.299), all of which contribute positively to yield. Indirectly, plant height at the harvesting stage positively affects the number of fruits per cluster (0.362) and yield per plant (0.219). At the same time, internodal length has a strong indirect effect on the number of flowers per cluster (0.521) and yield (0.343). Stem girth and the number of fruits per cluster also substantially indirectly impact yield per plant. The percentage of fruit set (-0.34), individual fruit weight (-0.108) and leaf area (-0.183) have the highest adverse effects. These findings highlight the importance of nutrient availability, such as phosphorus and nitrogen uptake, and growth traits, like plant height and the number of flowers, in optimizing cherry tomato yield. Fig. 4

Principle Component Analysis

The scree plot in this study shows that the first eigenvector had an eigenvalue greater than 1, explaining 85.9% of the total variation among growth, yield and quality parameters under different fertigation treatments. PC1, accounting for 86.2% of the variation, had positive loadings for most parameters except days from flowering (-0.951) (Table No. 4). Key contributors included fruit setting percentage (0.996), fruit length (0.99), total carotene (0.984), individual fruit weight (0.982), ascorbic acid (0.979) and yield per hectare (0.967). The scree plot suggests retaining the first three principal components, with the first two capturing most of the variation. Our findings follow those of previous studies. Fig. 5a

The factor loadings plot shows that most parameters significantly contribute to variance in PCA1. Parameters like the number of fruits per plant, number of flowers per cluster, soil available nitrogen, phosphorus, potassium and nutrient uptake (N, P, K) are strongly correlated with PCA2 Table No. 4b. Positive loadings in PC1 include fruit setting percentage (0.996), fruit length (0.99), total carotene (0.984), individual fruit weight (0.982), plant height (0.982), ascorbic acid (0.979), total sugar (0.977), dry matter production (0.976) and more. Days from flowering (-0.951) had a negative loading in PC1. Traits such as days to first flower appearance, plant height at harvest, number of fruits per cluster, yield, leaf area, total sugar and ascorbic acid showed a negative correlation in PCA2. Strong correlations between variables are indicated by their proximity in the biplot, with fruit weight, diameter and yield showing the strongest positive correlation and days to first flower and days to first harvest exhibited significant negative correlations, with longer dispersion for fruit weight and yield and lesser for fruit length. Similar findings were reported. Fig. 5b, 5c.

Discussion

Applying fertilizers through drip irrigation has gained popularity among developing countries, particularly India. It could help in the long run by providing efficient and uniform water and fertilizer applications. Drip irrigation and fertigation practices resulted in great success by increasing the yield of cherry tomatoes. Applying NPK fertilizer at the right time and in the correct amount enhances nitrogen availability in the soil, which is crucial for protein formation. Adequate protein levels support cell division and contribute to the development of tissues and organ growth. Nitrogen plays a critical role in stem growth as a vital protein component. The element is essential to cellular biomolecules such as nucleic acids, proteins, chlorophyll, and plant growth regulators. Plant growth reflects a crop's ability to use available resources efficiently (20). Water-soluble fertilizers resulted in the highest values for plant height, primary branches, internodal length and stem girth compared to surface irrigation. The increased irrigation frequency and optimized soil moisture under drip fertigation likely enhanced nutrient uptake and root development. This may have promoted indole-3-acetic acid (IAA) production, stimulating cell elongation and plant height (21). Efficient nitrogen use is crucial for chlorophyll and protein synthesis, further improving plant growth and stem girth. Days from bud appearance to fruit set and flowering to harvest were longer in the soil application than in fertigation treatments. This was likely due to nutrient loss through leaching or fixation in the soil, reducing water and nutrient uptake efficiency. The over-application of water and nutrients in the soil method further contributed to nutrient loss, leading to poor plant growth. In contrast, fertigation treatments resulted in higher numbers of clusters, flowers, fruits per cluster and fruit set percentage compared to the conventional method of fertilizer application, as supported by previous studies (22,23).

The largest leaf area per plant has been achieved with water-soluble fertilizers at 100% RDF consumed by fertigation (T_3). The rate of photosynthesis is primarily determined by leaf area, which effectively intercepts light energy and fixes CO_2, helping agricultural plants produce dry matter. Nitrogen's influence on leaf area is well documented and higher amounts are typically associated with enhanced growth. High readily available soil moisture and nutrients may contribute to boosting the role of adequate hydration for cell division, development and enlargement, resulting in increased leaf area. This inference aligns with the findings (24,25). The enhanced

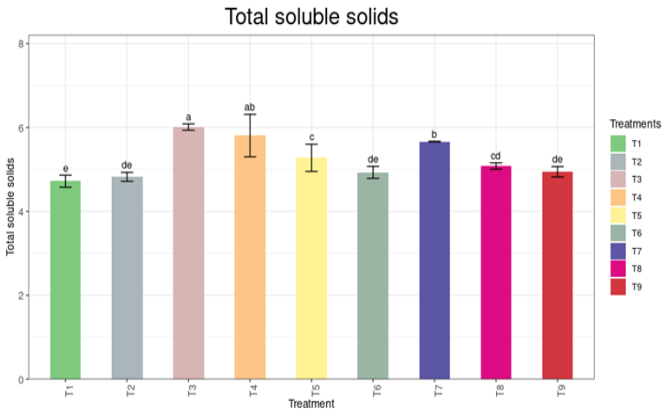

Figure. 3a

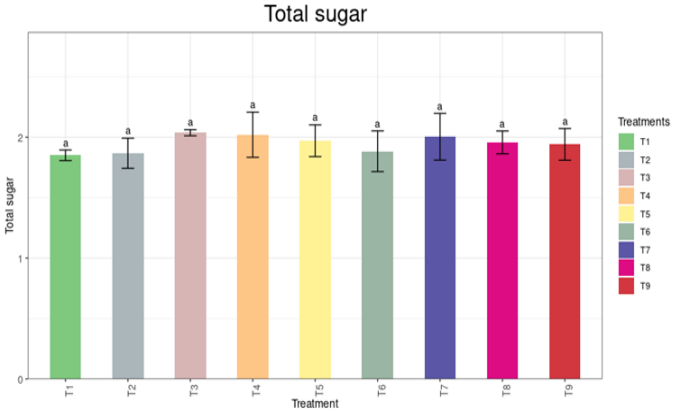

Figure. 3b

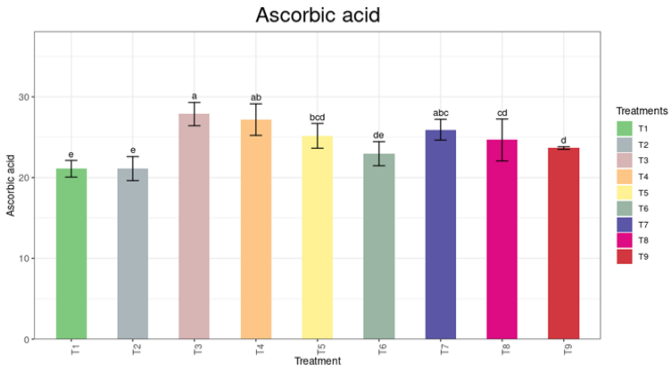

Figure. 3c

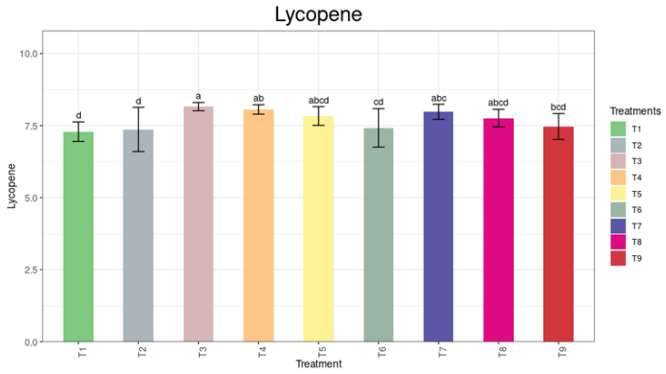

Figure. 3d

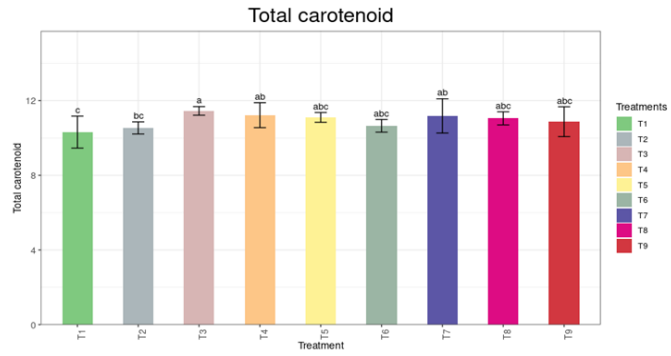

Figure. 3e

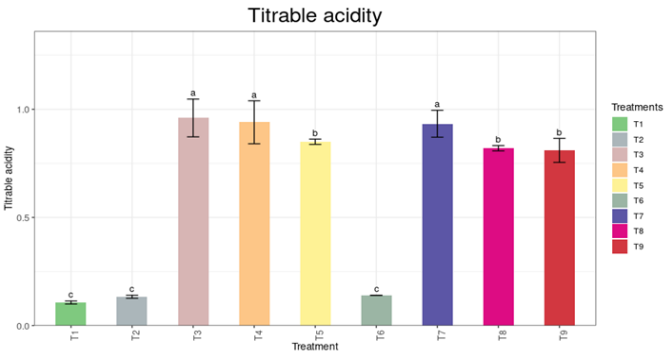

Figure. 3f

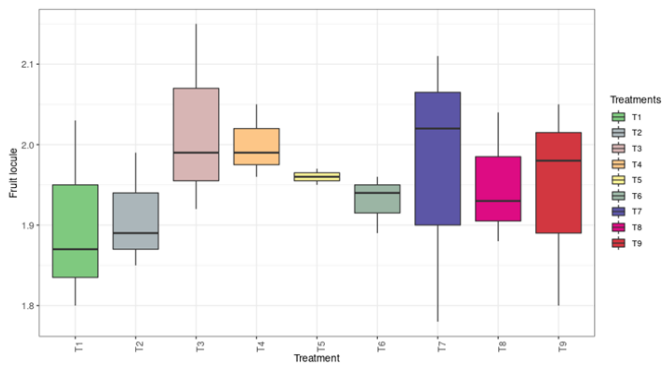

Figure. 3g

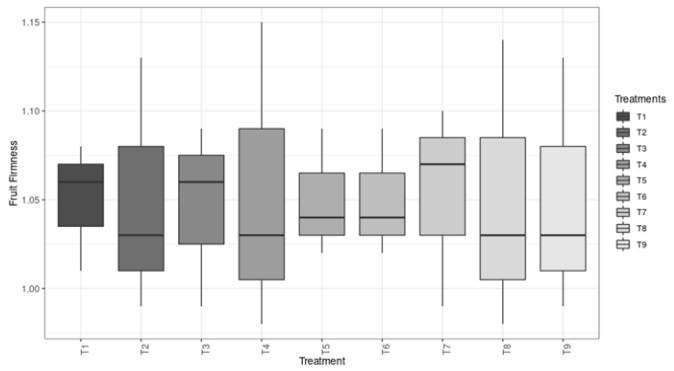

Figure. 3h

Fig. 3 Graphical representation compares productivity-enhancing traits, including Total soluble solids (2a), Total sugar (2b), Ascorbic acid (3c), Lycopene (3d), Beta-Carotenoid (2e), Titrable acidity (3f), Fruit locule (3g), Fruit firmness (3h).

Table 3: Effects of diverse fertigation treatments on the quality of cherry tomato

Treatments	TSS (^{0} Brix)	Total Sugar (mg/100g)	Ascorbic Acid (mg/100g)	Titrable acidity (mg/100g)	Lycopene (mg/100 g)	Total carotenoid (mg/100g)	Fruit locule	Fruit firmness	Shelf life
T_1	4.72^{d}	1.85	21.09^{e}	0.11^{c}	7.29	10.31^{d}	1.90	1.05	23
T_2	4.82^{d}	1.87	21.11^{e}	0.13^{c}	7.37	10.54^{cd}	1.91	1.05	23
T_3	6.01^{a}	2.04	27.87^{a}	0.96^{a}	8.16	11.45^{a}	2.02	1.05	23
T_4	5.81^{a}	2.02	27.18^{ab}	0.94^{a}	8.06	11.22^{ab}	2.00	1.05	23
T_5	5.28b^{c}	1.97	25.17^{bcd}	0.85^{b}	7.83	11.10^{ab}	1.96	1.05	23
T_6	4.93^{cd}	1.88	22.96^{de}	0.14^{c}	7.42	10.65^{bcd}	1.93	1.05	23
T_7	5.66^{ab}	2.00	25.93^{abc}	0.93^{a}	7.98	11.18^{ab}	1.97	1.05	23
T_8	5.08^{cd}	1.96	24.66^{bcd}	0.82^{b}	7.76	11.05^{abc}	1.95	1.05	23
T_9	4.94^{cd}	1.94	23.67^{cde}	0.81^{b}	7.47	10.87^{abcd}	1.94	1.05	23
SE (d)	0.08	0.07	0.79	0.03	0.28	0.41	0.07		
CV	2.18	5.13	4.83	7.23	5.52	5.63	5.54		
CD (5%)	0.16	0.14	1.64	0.06	0.59	0.86	0.15	NS	NS

*Significant at 5% level, CD: critical difference; SE: standard error, CV: Coefficient of Variation, NS-non-significant

T_1- Without Fertilizer Application

T_2 - Soil application with straight fertilizer @ 100% RDF

T_3- Fertigation with water-soluble fertilizers @ 100% RDF

T_4 - Fertigation with water-soluble fertilizers @ 75% RDF

T_5 - Fertigation with water-soluble fertilizers @ 50% RDF

T_6- Fertigation with water-soluble fertilizers @ 25% RDF

T_7- Soil application with SF @ 25% + Fertigation with WSF @ 75% RDF

T_8- Soil application with SF @ 50% + Fertigation with WSF @ 50% RDF

T_9- Soil application with SF @ 75% + Fertigation with WSF @ 25% RDF

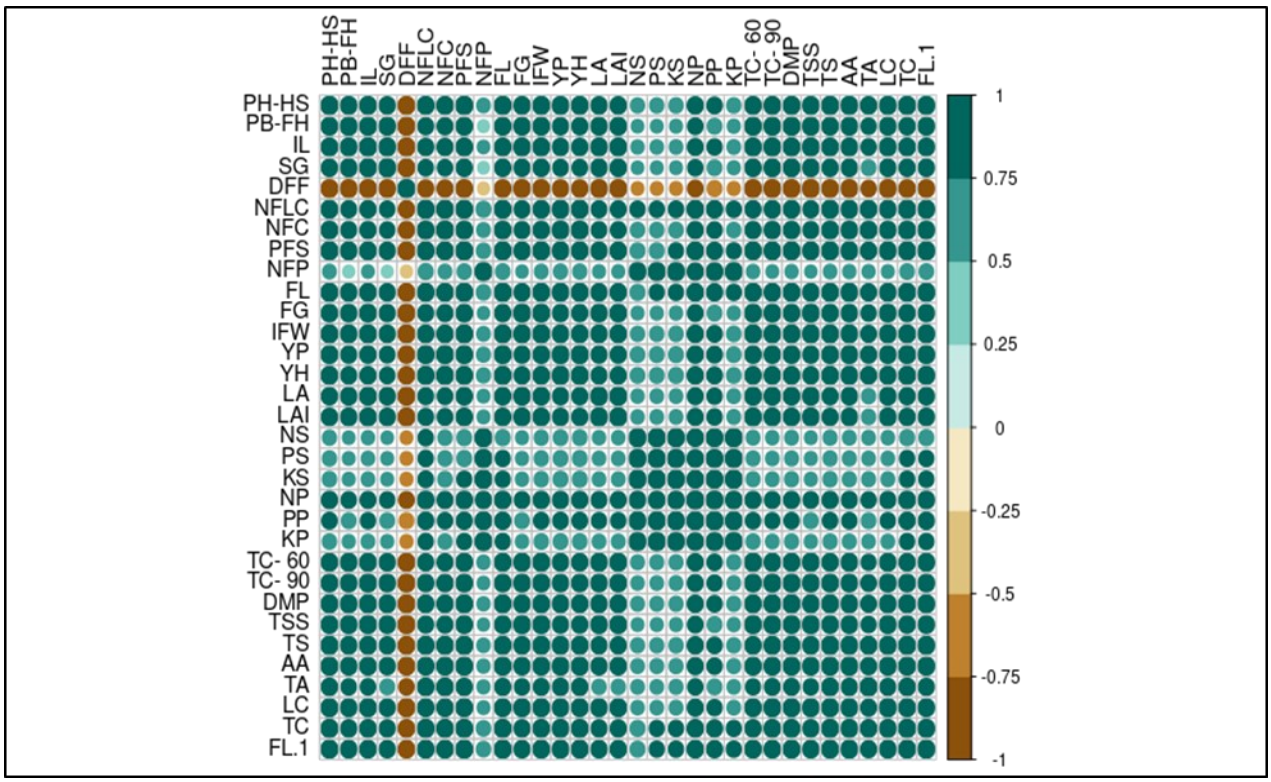

Fig. 4 Path Coefficient Analysis Correlograms

PH-HS - plant height at the harvesting stage, PB-FH - number of primary branches at the harvesting stage, IL- Inernodal length, SG - Stem girth, DFF - Days to First flowering, NFLC -Number of flowers per cluster, NFC -Number of fruit per cluster, PFS - Fruit setting percentage, NFP - Number of fruit per plant, FL -Fruit length, FG- Fruit girth, IFW - Individual fruit weight, YP- Yield per plant, YH -Yield per hectare, LA - leaf area, LAI - leaf area index, NS - Post-harvest soil available nitrogen, NP- Post-harvest soil available phosphorus, NK - Post-harvest soil available potassium, NP - Nitrogen uptake, PP - Phosphorus uptake, KP - potassium uptake, TC-60- Chlorophyll at 60 DAT, 2TC-90- Chlorophyll at 90 DAT, DMP - Dry matter production, LC - Lycopene, AA- Ascorbic acid, TSS - Total soluble solids, TS - Total sugar, TC- Total Carotenoid, TA- Titrable acidity, FL.1 – Fruit locule.

Table. 4 Principal component analysis for growth, yield, physiological and quality

	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Eigenvalue	27.577	3.071	0.756	0.221	0.152	0.11	0.065	0.049
% variance	86.177	9.598	2.361	0.69	0.475	0.343	0.154	0.154
Cumulative %	86.177	95.775	98.136	98.826	99.643	99.643	99.846	100

Table. 4a Principal component analysis for growth, yield, physiological and quality

Variables	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
PHHS	0.982	-0.112	0.099	0.037	-0.003	0.048	-0.099	-0.014
PBFH	0.939	-0.278	-0.096	0.096	0.043	0.094	0.046	0.094
IL	0.96	-0.22	-0.109	0.085	-0.045	-0.069	0.03	-0.055
SG	0.902	-0.256	-0.182	0.263	0.082	-0.076	0.043	-0.07
DFF	-0.951	0.283	0.088	-0.007	0.021	0.033	0.074	0.015
NFLC	0.971	0.096	0.204	-0.026	-0.016	-0.056	-0.038	0.038
NFC	0.95	-0.033	0.282	-0.088	0.04	-0.012	0.081	-0.018
PFS	0.996	-0.025	0.046	0.017	-0.013	0.053	-0.038	0.024
NFP	0.714	0.696	-0.068	-0.002	-0.023	0.03	-0.024	-0.009
FL	0.99	-0.003	0.039	0.023	0.102	0.079	0.017	-0.001
FG	0.94	-0.239	-0.11	-0.107	-0.187	0.026	0.017	-0.026
IFW	0.982	-0.113	-0.029	-0.024	-0.111	0.084	0.023	-0.05
YP	0.969	-0.022	0.162	-0.13	0.119	-0.014	0.038	-0.03
YH	0.967	-0.016	0.175	-0.141	0.11	-0.01	0.042	-0.022
LA	0.935	-0.185	-0.257	-0.121	0.05	-0.08	-0.033	0.016
LAI	0.937	-0.183	-0.253	-0.122	0.051	-0.076	-0.032	0.018
PHN	0.755	0.654	-0.041	-0.002	-0.023	-0.017	0.007	0.007
PHP	0.766	0.636	-0.065	0.002	0.01	-0.016	0.029	-0.05
PHK	0.778	0.626	-0.027	0.008	-0.014	-0.025	0.027	0.021
NP	0.948	0.304	-0.061	-0.015	-0.05	-0.002	-0.022	0.055
PP	0.886	0.448	-0.085	0.045	0.055	-0.006	-0.04	-0.001
KP	0.777	0.615	-0.12	0.038	-0.024	0.026	0.022	0.001
TC-60	0.961	-0.145	-0.169	-0.082	-0.006	0.135	0.035	-0.01
TC-90	0.966	-0.207	-0.029	0.018	-0.064	-0.087	0.103	0.034
DMP	0.976	-0.155	-0.015	0.103	0.026	0.006	0.046	0.103
TSS	0.949	-0.266	-0.135	-0.027	-0.074	0.043	0.009	-0.045
TS	0.977	-0.112	0.163	0.058	-0.056	0.008	-0.014	0.004
AA	0.979	-0.15	0.097	-0.031	0.086	0.039	-0.022	-0.013
TA	0.872	-0.026	0.468	0.097	-0.102	-0.003	-0.007	-0.005
LC	0.97	-0.193	0.026	-0.062	-0.063	-0.098	-0.038	0.055
TC	0.984	0.01	0.134	0.054	0.015	-0.08	-0.05	-0.032
FLO	0.974	-0.167	-0.034	0.059	0.083	0.08	-0.071	-0.014

PHHS - plant height at the harvesting stage, **PBFH** - number of primary branches at the harvesting stage, **IL-** Inernodal length, **SG** - Stem girth, **DFF** - Days to first flowering, **NFLC** -Number of flowers per cluster, **NFC** -Number of fruit per cluster, **PFS** - Fruit setting percentage, **NFP** - Number of fruit per plant, **FL** -Fruit length, **FG**- Fruit girth, **IFW** - Individual fruit weight, **YP**- Yield per plant, **YH** -Yield per hectare, **LA** - leaf area, **LAI** - leaf area index, **PHN** - Post-harvest soil available nitrogen, **PHP-** Post-harvest soil available phosphorus, **PHK** - Post-harvest soil available potassium, **NP** - Nitrogen uptake, **PP -** Phosphorus uptake, **KP -** potassium uptake, **TC-60-** Chlorophyll at 60 DAT, **TC-90-** Chlorophyll at 90 DAT, **DMP** - Dry matter production, **LC** - Lycopene, **AA**- Ascorbic acid, **TSS** - Total soluble solids, **TS** - Total sugar, **TC**- Total Carotenoid, **TA-** Titrable acidity, **FL** – Fruit locule.

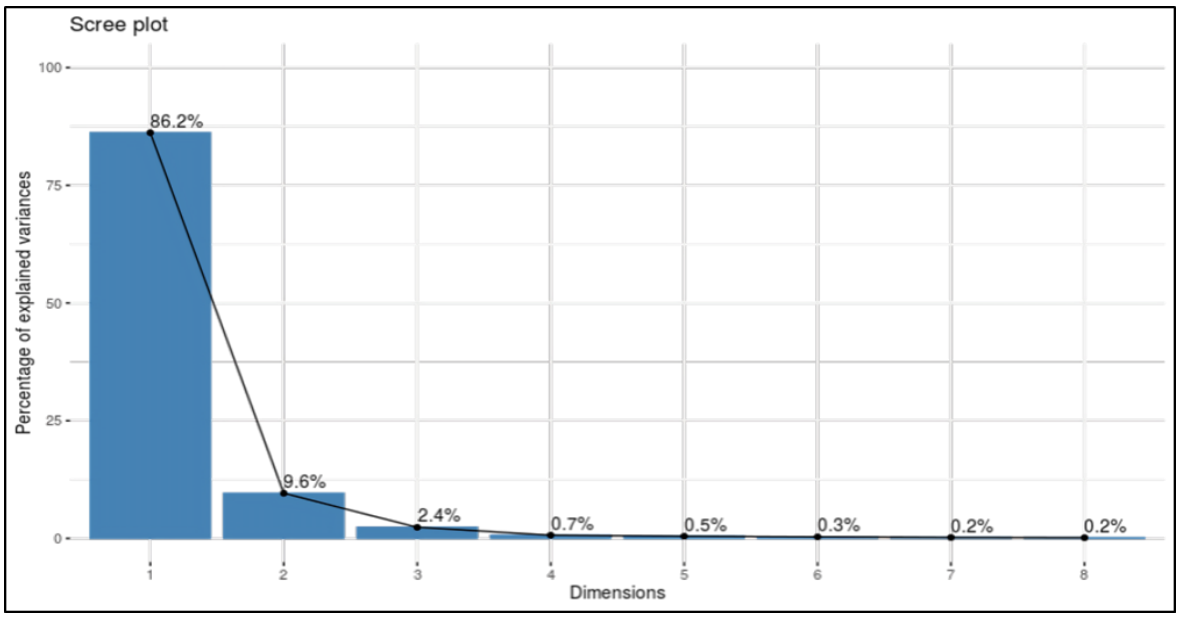

Fig. 5a. Scree plot reveals the number of components covering sufficient variation related to treatments used for investigated traits.

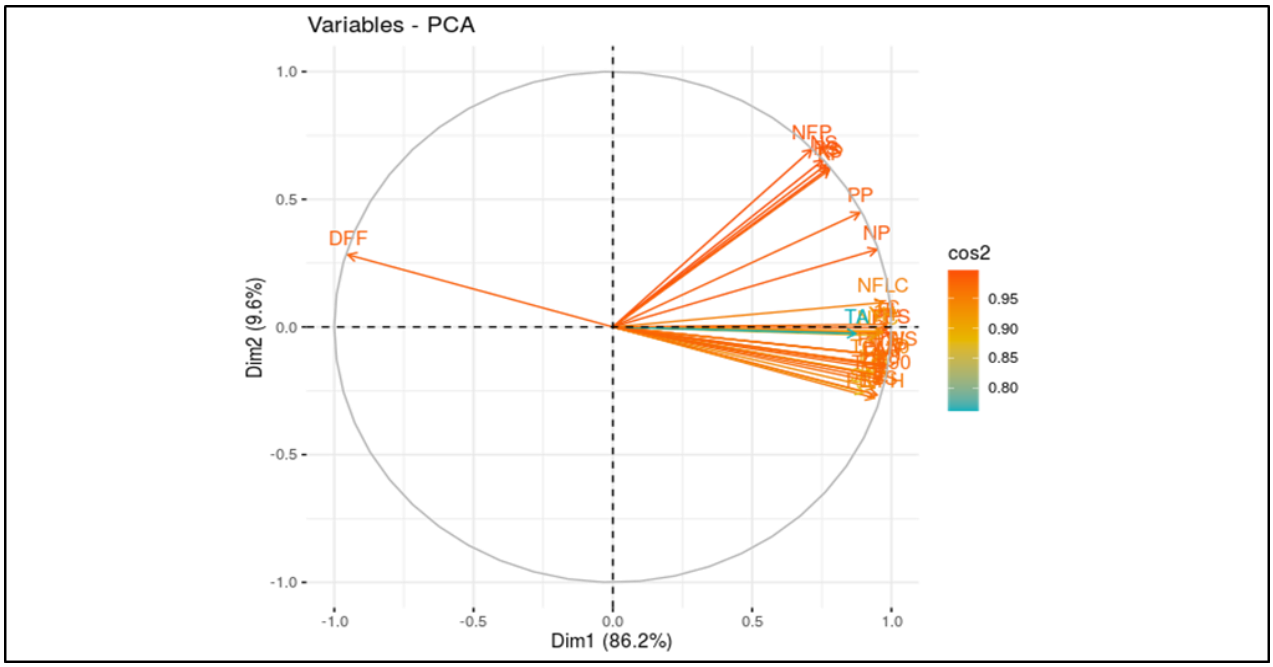

Fig. 5b. Biplot reveals the number of components covering sufficient variation related to treatments used for investigated traits

chlorophyll content found with drip fertigation treatment might be attributed to higher nutrient absorption, notably nitrogen. Several researchers have previously reported that increasing chlorophyll content with higher nutrition is possible for vegetable crops. The greater leaf area in the current experiment with the fertigation treatment at 100% RDF may have resulted in higher chlorophyll content (26,27). Different fertigation levels improved the production of dry matter. The fertigation level that produced the most significant amount of dry matter production was 100% RDF fertigation with water-soluble fertilizers. Increased nitrogen availability would have aided in improved protein synthesis, which would have led to the formation of more leaves and a more significant dry weight of leaves. Nitrogen treatment enhances the flow of metabolites from source to sink, which may account for its beneficial effect in encouraging plant development. Fertilizer application has a considerable impact on the buildup of dry biomass. A vital component for plant growth and development is phosphorus, 0.2% of a plant's dry matter weight. Our observations agree with the results of some previous findings (28, 29).

Applying fertilizer with 100% RDF through fertigation led to enhanced fruit length and diameter. Increased photosynthetic rates may have improved assimilate partitioning, resulting in longer and broader fruit. Fertigation treatments may increase fertilizer efficiency and nutrient absorption, resulting in greater values for these attributes (N, P, K). Optimal nutrient distribution produces growth hormones such as auxins, gibberellins and cytokinin, which improve nutrient absorption and water transport in assimilates, resulting in increased yield. The findings are consistent with those of this investigation (29,30).

The availability of potassium during the growing stages enhances the conversion of starch into simple sugars by activating the enzyme sucrose synthase, resulting in higher fruit sugar content. In plants with adequate potassium supply, the osmotic potential of the phloem sap and volume flow rate are elevated compared to those with low potassium levels, increasing sucrose concentration in well-nourished plants (31). Additionally, potassium maintains balanced electric charges in chloroplasts, promoting energy production in ATP and NADPH encouraging the synthesis of secondary metabolites like ascorbic acid (32). Increased potassium doses boost sugar content and enhance ascorbic acid levels in fruits (33). Potassium may inhibit the oxidation of ascorbic acid, allowing for greater storage in the fruits. Our findings align with previous studies (34-37).

Furthermore, microclimate parameters such as air temperature, relative humidity and photosynthetically active radiation were favourable in the NVP (Nutrient and Water Management Practices), positively influencing plant growth, yield and fruit quality traits, as noted (38). Fruits produced under NVP exhibited significantly higher dry matter content and total soluble solids. Certain tomato quality features, including total soluble solids (TSS), firmness and colour, were positively affected by specific water deficit levels (38). The increased ascorbic acid concentration with higher fertigation levels is attributed to enhanced nitrogen absorption, which is vital for ascorbic acid synthesis. These results are consistent with findings in cucumber and broccoli (39, 40).

Fertigation with water-soluble fertilizers at 100% RDF (T_3) showed higher total nitrogen uptake by crops. This increase could be due to reduced nitrogen losses and the favourable distribution of nitrogen near the plant roots, leading to better utilization of the applied nitrogen. The previous study reported that nitrate (NO_3-N) is highly mobile in the soil under fertigation, maintaining a higher concentration of NO_3-N at shallow depths (41). Increased nitrogen uptake with fertigation was also observed in tomatoes (42). Phosphorus uptake was also higher in the T_3 treatment (fertigation with water-soluble fertilizers at 100% RDF). This might be because phosphorus accumulation at shallow depths tends to be higher in fertigation treatments due to the frequency of fertigation and the complete solubility of phosphoric acid compared to soil application. These findings are consistent with those of investigations (43). The highest potassium uptake was observed in the treatment of fertigation with water-soluble fertilizers at 100% RDF (T_3). This higher uptake was due to significantly greater dry matter production and the absence of dilution of NPK as dry matter production per plant increased, with the concentration of nutrients in the plant following the trend of total uptake. The increase in potassium uptake was likely due to better nutrient availability in the root zone resulting from frequent nutrient applications and improved root activity. Additionally, reduced nutrient loss, primarily from leaching in fertigation compared to soil fertilizer application, contributed to this increase (44).

Efficient fertilizer use is essential for optimal growth and yield, making knowledge of soil nutrient availability crucial. In the present study, post-harvest soil nutrient levels were higher in the treatment of fertigation with water-soluble fertilizers at 100% RDF (T_3). This may be because the split application of water-soluble fertilizers under drip fertigation, according to crop requirements, allowed the crop to take up nutrients available at the root surface, thus not depleting many soil nutrients and maintaining optimal soil nutrient status. These results closely align with the findings in lettuce (45). Post-harvest soil nutrients were lower in the soil application of straight fertilizers at 100% RDF (T_1), as nutrients applied by soil application tended to leach into deeper layers, becoming unavailable to the crop and were lost from the soil due to leaching and volatilization (46).

Path coefficient analysis of cherry tomato growth reveals significant direct and indirect effects on yield. The number of flowers per cluster has the highest direct effect, followed by soil-available phosphorus, lycopene content, nitrogen uptake and ascorbic acid. Indirectly, plant height and internodal length influence yield positively, while traits like fruit set percentage, individual fruit weight and leaf area negatively affect yield. These findings emphasize the importance of nutrient availability and growth traits in enhancing cherry tomato yield (47, 48).

The scree plot and biplot indicate the first eigenvector captures a significant portion of the variation among growth, yield and quality parameters under different fertigation treatments. Key contributors include fruit setting percentage, fruit length and individual fruit weight. The analysis suggests retaining the first three principal components. The factor loadings plot shows strong correlations among traits like the number of fruits per plant and soil nutrient levels, with positive loadings for fruit setting percentage and negative loadings for days from flowering. (48-50)

Conclusion

The study demonstrated that fertigation with water-soluble fertilizers at 100% RDF significantly improved growth, yield and quality traits in cherry tomatoes grown in a protected environment. This method of nutrient delivery proved more efficient than conventional soil application, as it enhanced nutrient uptake, particularly nitrogen, phosphorus and potassium, which are essential for optimal plant growth. Increased plant height, leaf area, stem girth, fruit size and improved quality attributes like total soluble solids (TSS) and ascorbic acid were observed. Path coefficient analysis highlighted strong positive correlations between crucial growth parameters, such as plant height and yield, suggesting optimal fertigation enhances crop productivity. Principal component analysis (PCA) further identified essential traits such as fruit weight, number of fruits per plant and lycopene content as significant contributors to the variation observed across treatments.

Future research should optimize fertigation schedules for different cherry tomato cultivars by

experimenting with varying levels of nutrient doses, fertigation frequencies and timing. This could improve resource use efficiency and crop performance under various environmental conditions. Testing fertigation systems with other high-value crops would provide insight into its broader applicability. Incorporating modern technology, such as automated drip systems and real-time nutrient monitoring through IoT and AI, could enhance precision and scalability. Sustainable practices should also be integrated into fertigation, including organic amendments and bio-stimulants to boost nutrient uptake. Long-term studies are needed to evaluate the environmental impact of fertigation on soil health, water conservation, and nutrient leaching. By addressing these areas, fertigation could revolutionize modern agriculture, improving productivity, quality and sustainability, especially in resource-limited environments where maximizing efficiency is crucial.

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