**Synergistic effects of N P K fertilizer regimes and plant spacing on morphological and biochemical traits of bacterial wilt-resistant tomato lines (*Solanum lycopersicum* L.)**

**ABSTRACT**

Tomato *(Solanum lycopersicum* L.) is a heavy feeder of NPK nutrients, and precise management of fertilizer regimes and plant spacing is essential to maximize growth, yield, fruit quality, and disease resistance. Bacterial wilt, caused by *Ralstonia solanacearum* Smith, has become a limiting factor in the cultivation of tomato in some pockets of Zone-I and Zone-II of Himachal Pradesh (Kangra Valley and surrounding areas of Mandi and Chamba districts). This is a soil borne bacterial disease and results in complete failure of the crop. This disease has also been reported from traditional tomato growing areas of Solan and Kullu valleys of Himachal Pradesh. The present investigation was undertaken to study the effects of N, P, K fertilizer regimes and plant spacing on morphological and biochemical traits of bacterial wilt–resistant tomato lines. The trial was laid out in a split–split–plot design comprising three fertility levels—F₁: 75%, F₂: 100% NPK (100 kg N, 75 kg P₂O₅, 55 kg K₂O/ha), and F₃: 125%—in the main plot; three spacings—S₁: 45 cm×45 cm, S₂: 60 cm×45 cm, and S₃: 75 cm×45 cm—in subplots; and three varieties—V₁: DPT-1, V₂: DPT-2, and V₃: Palam Pink—in sub-subplots at the Vegetable Research Farm of the Department of Vegetable Science and Floriculture, CSK HPKV, Palampur during the summer-rainy season 2022. Observations included growth and yield traits (days to 50% flowering, days to first harvest, number of fruits per cluster, fruit harvest duration, plant height, average fruit weight, pericarp thickness, locule number, marketable yield per plant), and biochemical parameters (TSS, lycopene content, titrable acidity, ascorbic acid). The highest lycopene content was recorded in treatment F₂S₂V₂, while the highest ascorbic acid content was observed in F₃S₁V₁, both significantly superior to all other treatments. The highest marketable yield (1.65 kg/plant) was achieved in the F₃S₃V₁ treatment (125% NPK, 75 cm×45 cm spacing, DPT 1).

**Keywords: NPK fertilizer, Plant spacing, Pericarp thickness, Lycopene content, Ascorbic acid**

**Introduction**

Tomato (*Solanum lycopersicum* L.) is one of the most widely grown vegetables in the world. It is cultivated worldwide from tropic to temperate regions. Tomatoes are rich sources of vitamins A and C, along with essential minerals such as potassium and calcium. They are especially valued for their high lycopene content—a potent antioxidant known for its anticarcinogenic properties (Burton-Freeman & Reimers, 2011). Additionally, tomato fruits are excellent providers of ascorbic acid and stand as the second most significant source of vitamin C after citrus (Rao & Rao, 2007).

In India, where fresh fruits of tomato are in greater demand round the year, it is grown on an area of 849 thousand hectares with a production of 20,425 thousand metric tonnes and the productivity of 24.05 metric tonnes per hectare (NHB, 2023). Among Indian states, Andhra Pradesh leads in tomato production and area cultivated, with tomato ranking second only to potato in terms of national vegetable output. In Himachal Pradesh, it is the next most significant off-season crop after garden pea, offering substantial economic returns to growers during the rainy season in the plains. It occupies an area of 13.72 thousand hectares in Himachal Pradesh with the production of 474.34 thousand metric tonnes per hectare, respectively (NHB, 2024).

Tomato cultivation, however, faces significant challenges due to bacterial wilt. This disease, caused by *Ralstonia solanacearum*, poses a major threat in tropical and subtropical regions, resulting in substantial losses in various crops. To control its infection, several measures have been implemented but they have yielded minimum success (Davis, 2024).

Bacterial wilt presents a significant challenge for tomato cultivation in the Zone-I and Zone-II regions of Himachal Pradesh, which encompass Kangra Valley, Mandi, Chamba, Solan, and Kullu, frequently leading to total crop failures caused by this soil-borne pathogen. Farmers also face challenges such as the scarcity of high-yielding, stress- and disease-resistant cultivars, poor plant stands, and insufficient use of fertilizers and improved inputs (Tumwine et al., 2002; Waiganjo et al., 2006). According to Abdel-Mawgoud et al. (2007), fertiliser application and spacing are critical agronomic practices that substantially influence tomato yields. Fertilisers replenish the soil's macronutrients—nitrogen, phosphorus, and potassium—while optimal plant spacing ensures even light distribution, promotes air circulation, facilitates weeding, and supports overall plant development (Ibrahim, 2012).

Thus, the combination of adequate inorganic nutrition and appropriate plant spacing is crucial for maximizing tomato productivity. Addressing these factors, this study evaluated newly developed bacterial wilt–resistant tomato genotypes at the Vegetable Research Farm during the 2022 summer–rainy season, assessing fruit yield and key horticultural traits under varying NPK levels and spacing.

**Materials and Methods**

The present investigation was undertaken to study the effects of N, P, K fertilizer regimes and plant spacing on morphological and biochemical traits of bacterial wilt–resistant tomato lines (*Solanum* *lycopersicum* L.).

The experiment was laid out in Split-split plot design comprising of three fertility levels (F1 - 75% of NPK, F2 - 100% of NPK (100 kg N, 75 kg P2O5 and 55 kg K2O/ha and F3 - 125% of NPK) in main plot, three spacings (S1 - 45×45 cm, S2 - 60×45 cm and S3 - 75×45 cm) in sub plot and three varieties (V1 – DPT-1, V2 - DPT-2 and V3 - Palam Pink) at the Vegetable Research Farm of the Department of Vegetable Science and Floriculture, CSK Himachal Pradesh Krishi Vishvavidyalaya, Palampur during summer-rainy season 2022. The Vegetable Research Farm is situated at an elevation of 1,290.8 metre above mean sea level with 32°6’ N latitude, 76°3’ E longitude. It falls under mid hill zone of Himachal Pradesh. The area is agro-climatically situated in the mid-hill zone of Himachal Pradesh and features a humid, sub-temperate climate, with annual rainfall around 2,500 mm, most of which (70-80%) occurs from June to September. Weekly meteorological data on temperature, relative humidity, and rainfall was collected at the Agro-meteorological Laboratory of the Department of Agronomy, Forages and Grasslands Management, CSK HPKV, Palampur during the cropping season from February to June 2022.

The nursery bed (3 × 1 m, raised ~10–12 cm) was cleared, enriched with well-rotted farmyard manure (FYM), finely tilled, and sowed on 12 February 2022, with seeds lightly covered. The experimental field, ploughed thrice and pulverised, included drainage channels, and on 23 March 2022, seedlings of two bacterial-wilt-resistant lines (DPT-1, DPT-2) and the standard check Palam Pink were transplanted into subplots at spacings of 45×45 cm (12 plants), 60×45 cm (10 plants), and 75×45 cm (8 plants). FYM (20 t/ha) was combined with one-third of the nitrogen and full P₂O₅ and K₂O dose per treatment, followed by urea top-dressing in two splits (30 and 45 days after transplanting); treatments tested were 75%, 100%, and 125% of the recommended N (100 kg), P₂O₅ (75 kg), and K₂O (50 kg)/ha. Staking (bamboo, sutli, iron), removal of lower leaves during rains to prevent fruit rot, and standard intercultural operations were carried out. The other intercultural operations were carried out in accordance with recommended package of practices from time to time. The observations were recorded on growth and yield traits *viz*., days to 50 per cent flowering, days to first harvest, number of fruits per cluster, fruit harvest duration (days), plant height (cm), average fruit weight (g), pericarp thickness (mm), locules per fruit (No.), marketable yield per plant (kg), total soluble solids (°Brix), lycopene content (mg/100g), titrable acidity (%) and ascorbic acid (mg/100g). The data obtained from the experiment were analysed statistically using the standard procedures of Split-Split Block Design as described by Gomez and Gomez (1984) at 5% level of probability for the interpretation of results.

The data were recorded as below:

1. **Days to 50 per cent flowering**

Days to 50 per cent flowering were recorded from transplanting date to the date when 50 per cent plants in each replication in each entry had flowered.

1. **Days to first harvest**

Days to first harvest were recorded from transplanting date to the date when at least one marketable fruit was harvested in 50 per cent of the plants in each replication in each entry.

1. **Number of fruits per cluster**

Ten clusters in 10 competitive plants were taken at random and the number of fruits in each cluster were counted. Then the average number of fruits per cluster were calculated.

1. **Fruit harvest duration (days)**

The harvest duration was recorded by deducting the number of days to first picking from the days taken to the last picking.

1. **Plant height (cm)**

It was measured at the final stage of harvest from ground level to the tip of main shoot.

1. **Average fruit weight (g)**

Five fruits taken at random from 3rd and 4th pickings were weighed and averaged to obtain average fruit weight.

1. **Pericarp thickness (mm)**

The fruits used for recording of polar and equatorial diameters were also used to determine the pericarp thickness. The pericarp thickness was measured from an equatorial section of the fruits with the help of a scale and mean value were worked out.

1. **Locules per fruit (No.)**

The fruits were cut transversely and number of locules per fruit were recorded.

1. **Marketable yield per plant (kg)**

It was calculated as follows:

1. **Total soluble solids (°Brix)**

The total soluble solids was recorded under room temperature (20°C) with the help of “Digital Handheld Refractometer” by putting 1-2 drops of juice on the prism and taking the reading. The values recorded were expressed in °Brix (AOAC 1970).

1. **Lycopene content (mg/100g)**

Lycopene content of ripe tomato fruits was determined by ‘acetone-ether extraction method’ as suggested by Ranganna (2000).

**Procedure**

* About 10 g of fresh tomato pulp was placed in a mortar.
* The lycopene pigment was extracted with acetone by thorough mixing with a pestle and the extract was transferred into a 500 ml separation funnel containing 20 ml of petroleum ether (bp 40-60°C) followed by 20 ml of 5 per cent sodium sulphate solution, where two layers appeared.
* Extraction was repeated with different portions of petroleum ether until the product became colourless.
* The lower part was separated and the petroleum ether with the lycopene was passed into a brown bottle containing 10 g anhydrous sodium sulphate to absorb water and then kept aside for 30 minutes.
* Petroleum ether extract was then decanted into 100 ml volumetric flask.
* Sodium sulphate slurry was washed with petroleum ether until it became colourless.
* The extract was then transferred to a 100 ml volumetric flask and made to volume with petroleum ether.
* The absorbance of the petroleum ether extract was measured in a spectrophotometer (Model Spectronic-Genesys 5) at 503 nm using petroleum ether as blank.

Lycopene (mg/100g fruit pulp):

1. **Titrable acidity (%)**

Titrable acidity was determined according to the official method 942.15 (AOAC 2000). Five grams of tomato juice diluted in 25 ml of distilled water and titrated by 0.1N sodium hydroxide (NaOH) to pH 8.1. The titrable acidity was expressed as gram citric acid per kilogram of tomato, according to the following equation:

Here,

0.1 is the normality of NaOH (N),

0.064 is the conversion factor for citric acid

1. **Ascorbic acid (mg/100g)**

Ascorbic acid content was estimated at marketable red ripe fruit stage by ‘2,6-dichlorophenol-indophenol Visual Titration Method’ as described by Ranganna (1979).

**Reagents**

* 3 per cent meta-phosphoric acid (HPO3): Prepared by dissolving the sticks or pellets of HPO3 in glass distilled water.
* Ascorbic acid standard: 100 mg of L-ascorbic acid was weighed accurately and volume made up to 100 ml with 3 per cent HPO3. 10 ml of this solution was further diluted to 100 ml with 3 per cent HPO3. (1ml = 0.1mg ascorbic acid)

**Dye solution:** 50 mg of the sodium salt 2,6-dichlorophenol-indophenol was dissolved in approximately 150 ml of hot glass distilled water containing 42 mg of sodium bicarbonate. The solution was cooled and diluted with glass distilled water to 200 ml. Stored in a refrigerator and standardized every day.

**Procedure**

* 5 ml of standard ascorbic acid solution was taken in a beaker and 5 ml of HPO3 was added to it. The solution was titrated with the dye solution to a pink colour which persisted for 15 seconds.
* Dye factor (mg of ascorbic acid/ml of the dye) was determined by using the formula: =

Here,

* 0.5 means 0.5 mg of ascorbic acid in 5 ml of 100 ppm standard ascorbic acid solution,
* Titre = Volume of dye used to neutralize 5 ml of 100 ppm standard ascorbic acid solution along with 5 ml of meta-phosphoric acid.
* 10 g of macerated sample was blended with 3 per cent meta-phosphoric acid and the volume finally made up to 100 ml.
* Out of this 100 ml solution, 10 ml of solution was taken and titrated against 2,6-dichlorophenol-indophenol dye till the appearance of rose pink colour.
* The ascorbic acid content was calculated by using the following formula and was expressed as mg of ascorbic acid per 100 g of fresh sample.

Ascorbic acid content (mg/100g):

**Results and Discussion**

**Days to 50 per cent flowering**

The observations presented in Table 1 show that both the fertilizer levels and tomato varieties had a considerable effect on the number of days required to achieve 50% flowering. However, the plant spacing alone did not produce any significant impact. While the two-way combinations (fertilizer × spacing, fertilizer × variety, and spacing × variety) did not lead to notable variations, the interaction involving all three factors fertilizer dose, spacing, and variety was statistically significant.

Plants treated with 75% of the recommended NPK (F₁) flowered in the shortest duration (25.7 days), which was statistically at par with 100 per cent recommended NPK i.e., F2 fertilizer dose (26.0 days). In contrast, the 125% NPK level (F₃) resulted in delayed flowering (27.3 days), likely due to the enhanced vegetative growth encouraged by the surplus nitrogen. Among the three varieties, Palam Pink reached 50% flowering earliest (25.6 days), followed by DPT1 (25.9 days), with DPT2 being the slowest (27.6 days). These differences reflect genetic variation among the varieties in terms of flowering time.

In the three-way interaction (Table 2), flowering times ranged from 23.0 to 29.7 days. The earliest flowering (23.0 days) was recorded in the F₂S₁V₁ [F₂- 100% fertilizer dose (N (100 kg), P₂O₅ (75 kg), and K₂O (50 kg)/ha), S₁- 45cm x 45cm, V₁- DPT-1] treatment and was statistically on par with other combinations such as F₁S₁V₃ and F₂S₁V₃ (24.0 days). On the other hand, the longest flowering duration (29.7 days) was seen in F₃S₂V₁ and F₃S₃V₂.

These outcomes are in line with findings of Rashid et al. (2016) highlighted that higher fertilizer doses delay flowering, Kumar et al. (2021) emphasized varietal effects, and Amare and Gebremedhin (2020) reported that spacing had no significant impact. Conversely, Falodun and Emede (2019) found spacing to play a notable role in flowering time.

**Days to first harvest**

According to the data in Table 1, both plant spacing and variety had a marked influence on the number of days taken for the first harvest, while the effect of fertilizer levels was not statistically significant. Notably, significant interactions were observed for fertilizer × spacing and the three-way interaction of fertilizer × spacing × variety. However, no significant differences were recorded for the fertilizer × variety and spacing × variety interactions.

Among the spacing treatments, the shortest time to first harvest was observed under S₁ (72.8 days), followed by S₂ (73.7 days) and S₃ (74.1 days). This earlier maturity at closer spacing could be due to increased inter-plant competition for nutrients, air, and light, which may restrict vegetative growth and lead to earlier flowering. Regarding varieties, V₃ recorded the minimum days to first harvest (72.6 days), followed by V₂ (73.9 days) and V₁ (74.1 days).

The interaction between fertilizer dose and spacing (Table 2) revealed that the minimum days to first harvest (72.1 days) occurred in treatment F₂S₁. This was statistically on par with F₁S₃ (72.6 days), F₁S₁ (73.1 days), F₃S₁ (73.2 days), and F₁S₂ (73.4 days).

In the three-way interaction involving fertilizer dose, spacing, and variety (Table 4), the days to first harvest ranged from 71.0 (F₂S₁V₃) to 77.0 (F₂S₃V₂). The minimum duration to first harvest in F₂S₁V₃ was found statistically at par with sixteen other treatment combinations.

These findings are consistent with the study by Rashid et al. (2016), who reported that closer spacing leads to earlier fruiting, and with Islam et al. (2017), who observed significant varietal differences in the time to first fruit harvest.

The interaction between fertilizer dose and spacing (Table 2) revealed that the minimum days to first harvest (72.1 days) occurred in treatment F₂S₁. This was statistically on par with F₁S₃ (72.6 days), F₁S₁ (73.1 days), F₃S₁ (73.2 days), and F₁S₂ (73.4 days).

In the three-way interaction involving fertilizer dose, spacing, and variety (Table 4.), the days to first harvest ranged from 71.0 (F₂S₁V₃) to 77.0 (F₂S₃V₂). The minimum duration to first harvest in F₂S₁V₃ was statistically similar to sixteen other treatment combinations.

These findings are consistent with the study by Rashid et al. (2016), who reported that closer spacing leads to earlier fruiting, and with Islam et al. (2017), who observed significant varietal differences in the time to first fruit harvest.

**Table 1. Effect of fertilizer doses, spacing and varieties on days to 50 per cent flowering, days to first harvest, number of fruits per cluster and fruit harvest duration in tomato**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatment** | **Days to 50 per cent flowering** | **Days to first harvest** | **No. of fruits per cluster** | **Fruit harvest duration (days)** |
| **Fertilizer dose** | | | | |
| F1 | 25.7 | 73.0 | 4.0 | 34.6 |
| F2 | 26.0 | 73.6 | 4.3 | 34.8 |
| F3 | 27.3 | 74.0 | 4.2 | 35.4 |
| CD (Critical Difference) (5%) | 1.2 | NS | NS | NS |
| **Spacing** | | | | |
| S1 | 25.8 | 72.8 | 4.3 | 34.5 |
| S2 | 26.6 | 73.7 | 4.1 | 34.9 |
| S3 | 26.7 | 74.1 | 4.2 | 35.4 |
| CD (5%) | NS | 0.8 | NS | NS |
| **Variety** | | | | |
| V1 | 25.9 | 74.1 | 4.1 | 34.4 |
| V2 | 27.6 | 73.9 | 4.7 | 35.9 |
| V3 | 25.6 | 72.6 | 3.7 | 32.9 |
| CD (5%) | 0.7 | 0.9 | 0.3 | 1.0 |
| **Interactions** | | | | |
| F\*S | NS | 1.4 | NS | 2.0 |
| F\*V | NS | NS | NS | NS |
| S\*V | NS | NS | 0.6 | 1.9 |
| F\*S\*V | 2.0 | 2.7 | 1.0 | 3.1 |

**Table 2. Interaction effect of spacing with varieties for days to first harvest in tomato**

|  |  |  |  |
| --- | --- | --- | --- |
| **Days to first harvest** | | | |
| Fertilizer dose | Spacing | | |
| S1 | S2 | S3 |
| F1 | 73.1 | 73.4 | 72.6 |
| F2 | 72.1 | 73.9 | 74.7 |
| F3 | 73.2 | 73.8 | 75.0 |
| CD (P=0.05) |  | FS (1) | FS (2) |
|  |  | 1.4 | 1.9 |

F- Fertility levels: F1- 75% of recommended NPK, F2 -100% of recommended NPK, F3- 125% of recommended NPK; S- Spacings: S1- 45×45 cm, S1- 60×45 cm, S1- 75×45 cm; F\*S (1)- CD for fertilizer doses measures at same spacings and F\*S (2)- CD for spacings at same or different fertilizer doses.

**No. of fruits per cluster**

The number of fruits per cluster is a crucial factor influencing the total fruit yield of a plant. Analysis of Table 1 revealed that variety had a significant impact on this trait, while the effects of fertilizer dose and plant spacing were not statistically significant. However, interactions between spacing × variety and the three-way interaction involving fertilizer dose × spacing × variety were significant. The two-way interactions of fertilizer × spacing and fertilizer × variety did not show significant effects.

Among the varieties, V₂ produced the highest number of fruits per cluster (4.7), followed by V₁ (4.1) and V₃ (3.7), suggesting that DPT-2 (V₂) was more productive in terms of cluster fruit count. The interaction between spacing and variety (Table 3) showed that the highest number of fruits per cluster (4.8) occurred in S₂V₂, which was statistically similar to S₃V₂ and S₁V₂ (both 4.7), as well as S₁V₁ (4.4).

For the three-way interaction of fertilizer dose × spacing × variety (Table 16), fruit count per cluster ranged from 3.3 (F₃S₂V₃) to 5.7 (F₃S₁V₂). The treatment F₃S₁V₂ was statistically comparable with F₁S₂V₂, F₂S₂V₁, and F₂S₃V₂ (all 5.0), along with F₂S₁V₁, F₂S₂V₂, and F₃S₂V₂ (all 4.7).

These results align well with those of Balemi (2008), who found significant differences in the number of fruits per cluster based on variety. Prodhan (2011) also reported that spacing had a marked influence on this trait in tomato.

**Table 3. Interaction effect of spacing with varieties for number of fruits per cluster in tomato**

|  |  |  |  |
| --- | --- | --- | --- |
| **No. of fruits per cluster** | | | |
| Spacing | Variety | | |
| V1 | V2 | V3 |
| S1 | 4.4 | 4.7 | 3.7 |
| S2 | 4.0 | 4.8 | 3.4 |
| S3 | 3.8 | 4.7 | 4.1 |
| CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.6 | 0.6 |

S- Spacings: S1- 45×45cm, S2- 60×45cm, S3- 75×45cm; V- Varieties: V1- DPT-1, V2-DPT-2, V3- Palam Pink; S\*V (1)- CD for spacings measures at same varieties and S\*V (2)- CD for varieties at same or different spacings.

**Fruit harvest duration (days)**

A longer fruit harvest duration is desirable as it contributes to a higher total marketable yield in tomato. According to Table 1, the duration of fruit harvest was significantly influenced by the variety, whereas fertilizer dose and spacing had no statistically significant effect. All interaction effects except fertilizer dose × variety were found to be significant.

Among the varieties, V₂ exhibited the longest fruit harvest duration (35.9 days), followed by V₁ (34.4 days) and V₃ (32.9 days). The interaction between fertilizer dose and spacing (Table 4) showed that the maximum harvest duration was recorded under F₃S₃ (36.7 days), which was statistically at par with F₃S₂ (36.3 days), F₂S₃ (35.8 days), F₂S₁ (35.6 days), F₁S₂ (35.4 days), and F₁S₁ (34.8 days).

Regarding the spacing × variety interaction (Table 4), the longest fruit harvest duration was observed in S₃V₂ (36.9 days), which was statistically comparable to S₁V₂ (36.8 days), S₂V₁ (36.2 days), and S₃V₁ (35.7 days). The three-way interaction of fertilizer dose × spacing × variety (Table 16) showed that fruit harvest duration ranged from 30.0 days (F₃S₁V₁) to 37.7 days (F₃S₃V₁). As many as sixteen other treatment combinations were also statistically at par with F₃S₃V₁.

These results differ from the findings of Dhiman et al. (2018) and Gill et al. (2018), who observed no significant effect of fertilizer on fruit harvest duration.

**Table 4. Interaction effect of fertilizer doses with spacing and spacing with varieties for fruit harvest duration in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Fruit harvest duration (days)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 34.8 | 35.4 | 33.7 | S1 | 34.2 | 36.8 | 32.4 |
| F2 | 35.6 | 33.0 | 35.8 | S2 | 36.2 | 34.2 | 34.3 |
| F3 | 33.1 | 36.3 | 36.7 | S3 | 35.7 | 36.9 | 33.6 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 1.5 | 2.0 |  |  | 1.8 | 1.7 |

F- Fertility levels : F1- 75% of recommended NPK, F2 -100% of recommended NPK, F3- 125% of recommended NPK; S- Spacings : S1- 45×45cm, S2- 60×45cm, S3- 75×45cm; V- Varieties: V1- DPT-1, V2-DPT-2, V3- Palam Pink; F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

**Plant Height (cm)**

In areas prone to heavy rainfall, indeterminate tomato cultivars are preferred over semi-determinate and determinate types. This preference arises because, in mid-hill regions, the fruiting period of tomato often overlaps with the rainy season, leading to severe losses due to fruit rot. Determinate varieties are more vulnerable to such diseases compared to semi-determinate and indeterminate ones.

As per Table 5, fertilizer dose, plant spacing, and variety had significant effects on plant height. Furthermore, the interactions between fertilizer dose × spacing and the three-way interaction involving fertilizer dose × spacing × variety were also significant. However, the two-way interactions—fertilizer dose × variety and spacing × variety did not show significant variation.

Among fertilizer treatments, the tallest plants were recorded under F₃ (93.1 cm), followed by F₂ (90.1 cm) and F₁ (89.0 cm). This trend might be attributed to higher nitrogen levels in F₃, which promote vegetative growth and stimulate auxin and gibberellin activity, contributing to increased plant height.

Considering spacing treatments, S₃ produced the tallest plants (92.9 cm), followed by S₂ (90.8 cm) and S₁ (88.5 cm). This may be due to reduced plant to plant competition in wider spacing (S₃), allowing for more uniform and taller growth.

Among the varieties, V₂ had the maximum plant height (100.7 cm), statistically at par with V₁ (99.6 cm). These variations are likely the result of different growth habits inherent to each variety.

The interaction of fertilizer dose × spacing (Table 6) revealed that F₃S₃ resulted in the tallest plants (98.2 cm), significantly taller than other treatment combinations. The three-way interaction (Table 16) showed plant height ranged from 69.3 cm to 110.7 cm. The tallest plants were observed in F₃S₃V₁, which was statistically similar to F₂S₁V₂ (108.7 cm) and F₃S₃V₂ (103.7 cm).

These findings are in agreement with earlier reports by Rashid et al. (2016), Pilote et al. (2024) and Balemi (2008) for fertilizer effect, Amare and Gebremedhin (2020) for spacing, and Falodun and Emede (2019) for varietal differences in plant height.

**Table 5. Effect of fertilizer doses, spacing and varieties on plant height, average fruit weight, pericarp thickness and locules per fruit in tomato**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Treatment** | **Plant height (cm)** | **Average fruit weight (g)** | **Pericarp thickness (mm)** | **Locules per fruit (No.)** |
| **Fertilizer dose** | | | |  |
| F1 | 89.0 | 77.3 | 5.7 | 3.8 |
| F2 | 90.1 | 79.2 | 5.6 | 4.0 |
| F3 | 93.1 | 80.0 | 5.5 | 4.1 |
| CD(5%) | 2.6 | 1.0 | 0.2 | 0.2 |
| **Spacing** | | | |  |
| S1 | 88.5 | 77.2 | 5.9 | 4.0 |
| S2 | 90.8 | 79.0 | 5.5 | 3.9 |
| S3 | 92.9 | 80.3 | 5.8 | 4.1 |
| CD(5%) | 2.1 | 0.6 | 0.2 | NS |
| **Variety** | | | |  |
| V1 | 99.6 | 80.2 | 5.4 | 4.1 |
| V2 | 100.7 | 78.3 | 5.6 | 3.8 |
| V3 | 71.9 | 78.0 | 5.8 | 4.1 |
| CD(5%) | 3.3 | 0.8 | 0.1 | 0.2 |
| **Interactions** | | | |  |
| F\*S | 3.6 | 1.1 | 0.3 | 0.3 |
| F\*V | NS | NS | NS | NS |
| S\*V | NS | 1.4 | 0.3 | 0.4 |
| F\*S\*V | 7.2 | 2.4 | 0.4 | 0.7 |

**Table 6. Interaction effect of fertilizer dose with spacing for plant height in tomato**

|  |  |  |  |
| --- | --- | --- | --- |
| **Plant height (cm)** | | | |
| Fertilizer dose | Spacing | | |
| S1 | S2 | S3 |
| F1 | 88.2 | 88.2 | 90.6 |
| F2 | 89.3 | 91.2 | 89.8 |
| F3 | 88.0 | 93.0 | 98.2 |
| CD (P=0.05) |  | FS (1) | FS (2) |
|  |  | 3.7 | 3.6 |

F- Fertility levels: F1- 75% of recommended NPK, F2 -100% of recommended NPK, F3- 125% of recommended NPK; S- Spacings: S1- 45×45 cm, S1- 60×45 cm, S1- 75×45 cm; F\*S (1)- CD for fertilizer doses measures at same spacings and F\*S (2)- CD for spacings at same or different fertilizer doses.

**Average fruit weight (g)**

A perusal of data from table 5 showed that all the factors under study i.e., fertilizer doses, spacings and varieties, and all the interactions except fertilizer doses × varieties were found significant.

Among the fertilizer treatments, fruits from F₃ had the highest average weight (80.0 g), which was statistically at par to those from F₂ (79.2 g). The lowest average fruit weight (77.3 g) was recorded under F₁. The observed increase in fruit weight with higher fertilizer levels is likely linked to improved vegetative growth and physiological activity, resulting in enhanced fruit size and weight. In terms of spacing, S₃ yielded the heaviest fruits (80.3 g), which was significantly superior to S₂ (79.0 g) and S₁ (77.2 g). Among the varieties, V₁ produced the highest average fruit weight (80.2 g), followed by V₂ (78.3 g) and V₃ (78.0 g).

The interaction between fertilizer dose and spacing (Table 7) showed that the highest average fruit weight (81.2 g) was recorded in F₃S₃, which was statistically on par with F₂S₃ (80.4 g). The lowest average fruit weight (74.4 g) was observed in F₁S₁. For the spacing × variety interaction (Table 7), the highest average fruit weight (81.9 g) occurred in S₃V₁ and was statistically similar to S₃V₂ (80.6 g). The lowest value (75.2 g) was found in S₁V₂. The three-way interaction (Table 16) for average fruit weight varied from 72.5 g (F₁S₁V₃) to 83.8 g (F₃S₃V₁), with F₃S₃V₁ being statistically at par with F₂S₃V₁ (81.5 g).

These findings are consistent with those of Balemi (2008), who observed that higher fertilizer doses improved fruit weight. The role of genetic differences in influencing fruit size has also been noted by Balemi (2008) and Gill et al. (2018).

**Table 7. Interaction effect of fertilizer doses with spacing and spacing with varieties for average fruit weight in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Average fruit weight (g)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 74.4 | 78.2 | 79.2 | S1 | 78.4 | 75.2 | 77.9 |
| F2 | 77.8 | 79.3 | 80.4 | S2 | 80.2 | 79.1 | 77.8 |
| F3 | 79.3 | 79.6 | 81.2 | S3 | 81.9 | 80.6 | 78.3 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV(1) | SV(2) |
|  |  | 1.1 | 1.3 |  |  | 1.4 | 1.3 |

**Table 8. Interaction effect of fertilizer doses with spacing and spacing with varieties for pericarp thickness in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Pericarp thickness (mm)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 5.5 | 5.5 | 6.2 | S1 | 5.2 | 5.6 | 5.7 |
| F2 | 5.8 | 5.7 | 5.3 | S2 | 5.3 | 5.6 | 5.6 |
| F3 | 5.2 | 5.3 | 5.9 | S3 | 5.8 | 5.7 | 6.0 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.3 | 0.3 |  |  | 0.2 | 0.3 |

F- Fertility levels : F1- 75% of recommended NPK, F2 -100% of recommended NPK, F3- 125% of recommended NPK; S- Spacings : S1- 45×45cm, S2- 60×45cm, S3- 75×45cm; V- Varieties: V1- DPT-1, V2-DPT-2, V3- Palam Pink; F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

**Pericarp thickness (mm)**

A thicker pericarp is advantageous in tomatoes as it provides better resistance to handling, transportation shocks, and contributes to longer shelf life by maintaining fruit firmness. According to the data in Table 5, fertilizer dose, plant spacing, and variety significantly influenced pericarp thickness. Among interaction effects, fertilizer dose × spacing and spacing × variety were found to be significant, whereas the fertilizer dose × variety interaction was not. The combined three-way interaction of fertilizer dose × spacing × variety was also significant.

Among fertilizer treatments, the maximum pericarp thickness was observed in F₁ (5.7 mm), which was statistically similar to F₂ (5.6 mm). Regarding spacing, S₃ produced fruits with the thickest pericarp (5.8 mm), significantly thicker than those grown under S₁ and S₂ (both 5.5 mm). Among the varieties, V₃ had the highest pericarp thickness (5.8 mm), followed by V₂ (5.6 mm) and V₁ (5.4 mm).

From the fertilizer dose × spacing interaction (Table 8), the highest pericarp thickness was recorded in F₁S₃ (6.2 mm), which was statistically on par with F₃S₃ (5.9 mm) but superior to all other combinations.

In terms of spacing × variety interaction (Table 8), the maximum pericarp thickness (6.0 mm) was noted in S₃V₃. This was statistically at par with S₃V₁ (5.8 mm), S₁V₃ and S₃V₂ (both 5.7 mm).

The three-way interaction (Table 16) revealed a pericarp thickness range from 4.9 mm (F₂S₃V₂) to 6.7 mm (F₂S₁V₃). The thickest pericarp was recorded in F₂S₁V₃, which was statistically comparable to F₁S₃V₂ (6.5 mm) and F₃S₃V₁ (6.3 mm).

These results align with the findings of Krishnan and Indiresh (2015) regarding the influence of fertilizer, Singh et al. (2018) on spacing, and Abriham and Kefale (2020) on varietal differences in pericarp thickness.

**Locules per fruit (No.)**

Tomato fruits with fewer locules are generally preferred as they tend to have firmer flesh, making them more suitable for transport and storage. As per the data presented in Table 5, both fertilizer dose and variety had a significant impact on the number of locules per fruit, while spacing had no noticeable effect.

**Table 9. Interaction effect of fertilizer doses with spacing and spacing with varieties for locules per number in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Locules per fruit (No.)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 3.8 | 3.6 | 3.9 | S1 | 4.0 | 4.1 | 3.9 |
| F2 | 4.0 | 3.7 | 4.2 | S2 | 4.3 | 3.6 | 3.6 |
| F3 | 4.2 | 4.2 | 4.0 | S3 | 3.9 | 3.6 | 4.7 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.3 | 0.3 |  |  | 0.4 | 0.4 |

F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

Fertilizer could influence the internal hormone levels (particularly auxin, cytokinin, and GA), which in turn may impact the development of ovaries and locules. An excess of nitrogen can enhance the production of auxin, potentially encouraging the formation of additional carpels and, consequently, more locules.

Among interaction effects, fertilizer dose × spacing and spacing × variety were significant, whereas fertilizer dose × variety was non-significant. The three-way interaction of fertilizer dose × spacing × variety also showed significant variation.

Among fertilizer levels, F₁ resulted in the fewest locules per fruit (3.8), which was statistically at par with F₂ (4.0) but significantly lower than F₃ (4.1). Among varieties, V₂ recorded the lowest number of locules (3.8), followed by V₁ and V₃ (both 4.1), suggesting that V₂ is better suited for producing firmer fruits. For the interaction between fertilizer dose and spacing (Table 9), F₁S₂ showed the fewest locules (3.6), statistically at par with F₂S₂ (3.7), F₂S₁, and F₁S₃ (both 3.9).The spacing × variety interaction (Table 9) indicated that the lowest number of locules per fruit (3.6) was observed in S₂V₂, S₂V₃, and S₃V₂, statistically similar to S₃V₁, S₁V₃ (both 3.9), and S₁V₁ (4.0).

The three-way interaction (Table 16) revealed a range in locule number from 2.9 (F₁S₂V₂) to 5.3 (F₂S₃V₃). The treatment F₁S₂V₂ was statistically at par with F₂S₃V₂ (3.3), F₁S₂V₃ (3.4), and both F₂S₂V₂ and F₃S₃V₁ (3.5).

These findings agree with the results reported by Oko-Ibom and Asiegbu (2007), who also noted significant effects of fertilizer and variety on locule count. However, they contrast with the findings of Krishnan and Indiresh (2015), who reported a non-significant fertilizer effect, and Singh et al. (2018), who found spacing to significantly influence this trait.

**Marketable yield per plant (kg)**

Marketable yield refers to the weight of healthy, undamaged fruits that can be sold at a profitable rate. According to the data in Table 10, fertilizer doses, plant spacing, and variety all had a significant impact on marketable yield per plant. Among the interaction effects, all were statistically significant except for fertilizer dose × variety. Among fertilizer treatments, the highest marketable yield per plant (1.37 kg) was achieved with F₃, followed by F₂ (1.29 kg), both of which were significantly superior to F₁ (1.15 kg). In terms of spacing, S₃ produced the maximum yield (1.35 kg), significantly greater than S₂ (1.28 kg) and S₁ (1.19 kg). Among the varieties, V₂ produced the highest yield (1.39 kg), which was statistically similar to V₁ (1.38 kg); both were significantly superior to V₃ (1.05 kg).

The fertilizer dose × spacing interaction (Table 11) revealed that the maximum yield per plant was recorded in F₃S₃ (1.48 kg), statistically at par with F₃S₂ (1.40 kg).

In the spacing × variety interaction (Table 11), the highest yield (1.49 kg) was recorded in S₃V₂, which was statistically similar to S₃V₁ (1.48 kg) and S₂V₂ (1.44 kg).

The three-way interaction (Table 17) showed that marketable yield per plant ranged from 0.85 kg (F₁S₁V₃) to 1.65 kg (F₃S₃V₁). The highest yield was observed in F₃S₃V₁, statistically comparable to F₃S₃V₂ (1.64 kg), F₃S₂V₂ (1.56 kg), and F₃S₂V₁ (1.54 kg).

These findings support those of Amare and Gebremedhin (2020) and Law-Ogbomo and Egharevba (2008), who also found significant effects of spacing on yield. However, they differ from the results of Balemi (2008), who reported that cultivar had no significant effect on marketable yield.

**Total soluble solids (°Brix)**

Total soluble solids (TSS) are a key quality parameter for processing tomatoes, as even a slight increase in °Brix can significantly improve product yield and reduce energy costs during concentration processes. Data from Table 10 showed that fertilizer doses, plant spacing, and varieties all had a significant effect on TSS content. All interaction effects, except for fertilizer dose × variety, were also found to be significant.

**Table 10. Effect of fertilizer doses, spacing and varieties on marketable yield per plant, total soluble solids, lycopene content and titrable acidity and ascorbic acid in tomato**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Treatment** | **Marketable yield per plant (kg)** | **Total soluble solids (°Brix)** | **Lycopene content (mg/100g)** | **Titrable acidity (%)** | **Ascorbic acid (mg/100g)** |
| **Fertilizer doses** | | | | | |
| F1 | 1.15 | 4.49 | 2.97 | 0.267 | 13.7 |
| F2 | 1.29 | 4.66 | 4.28 | 0.287 | 13.2 |
| F3 | 1.37 | 4.94 | 2.56 | 0.307 | 13.8 |
| CD(5%) | 0.08 | 0.05 | 0.02 | 0.005 | NS |
| **Spacing** | | | | | |
| S1 | 1.19 | 4.61 | 2.97 | 0.273 | 14.1 |
| S2 | 1.28 | 4.70 | 3.76 | 0.297 | 13.6 |
| S3 | 1.35 | 4.77 | 3.07 | 0.290 | 12.9 |
| CD(5%) | 0.04 | 0.09 | 0.03 | 0.004 | 0.4 |
| **Varieties** | | | | | |
| V1 | 1.38 | 4.44 | 3.34 | 0.285 | 14 |
| V2 | 1.39 | 4.89 | 2.94 | 0.286 | 13.5 |
| V3 | 1.05 | 4.76 | 3.52 | 0.290 | 13.1 |
| CD(5%) | 0.04 | 0.10 | 0.03 | 0.004 | 0.2 |
| **Interactions** | | | | | |
| F\*S | 0.09 | 0.14 | 0.05 | 0.007 | NS |
| F\*V | NS | NS | NS | NS | NS |
| S\*V | 0.06 | 0.17 | 0.05 | 0.010 | 0.5 |
| F\*S\*V | 0.11 | 0.30 | 0.08 | 0.011 | 0.7 |

F\*S (1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Marketable yield per plant (kg)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 1.03 | 1.17 | 1.26 | S1 | 1.26 | 1.23 | 1.09 |
| F2 | 1.31 | 1.26 | 1.30 | S2 | 1.39 | 1.44 | 1.00 |
| F3 | 1.24 | 1.40 | 1.48 | S3 | 1.48 | 1.49 | 1.07 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.06 | 0.09 |  |  | 0.07 | 0.06 |

**Table 11. Interaction effect of fertilizer doses with spacing and spacing with varieties for marketable yield per plant in tomato**

F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

Among the fertilizer treatments, F₃ yielded the highest TSS (4.94 °Brix), followed by F₂ (4.66 °Brix) and F₁ (4.49 °Brix). In terms of spacing, the maximum TSS (4.77 °Brix) was recorded under S₃, which was statistically comparable to S₂ (4.70 °Brix), while the lowest value was seen under S₁ (4.61 °Brix). Among varieties, V₂ had the highest TSS (4.89 °Brix), followed by V₃ (4.76 °Brix) and V₁ (4.44 °Brix).

**Table 12. Interaction effect of fertilizer doses with spacing and spacing with varieties for total soluble solids in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Total soluble solids (°Brix)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 4.42 | 4.40 | 4.65 | S1 | 4.30 | 4.72 | 4.80 |
| F2 | 4.48 | 4.92 | 4.56 | S2 | 4.68 | 4.78 | 4.65 |
| F3 | 4.92 | 4.80 | 5.10 | S3 | 4.34 | 5.15 | 4.83 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV(1) | SV(2) |
|  |  | 0.16 | 0.14 |  |  | 0.18 | 0.17 |

F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

The fertilizer dose × spacing interaction (Table 12) revealed that the highest TSS (5.10 °Brix) was found in F₃S₃, which was significantly higher than all other combinations. The lowest value (4.40 °Brix) was recorded in F₁S₂. For the spacing × variety interaction (Table 12), the highest TSS (5.15 °Brix) was recorded in S₃V₂, significantly superior to other combinations. The lowest value (4.30 °Brix) was noted in S₁V₁.

The three-way interaction (Table 17) revealed that TSS ranged from 3.81 °Brix (F₁S₃V₁) to 6.06 °Brix (F₃S₃V₂). The highest TSS observed in F₃S₃V₂ was statistically comparable to F₂S₂V₂ (5.87 °Brix).

These findings are consistent with the results of Abdel-Mawgoud et al. (2007), Fandi et al. (2010), Kumar et al. (2013), and Sabit (2020), who reported that fertilizer significantly affects TSS. Oko-Ibom and Asiegbu (2007) also documented substantial varietal effects on TSS in tomato.

**Lycopene content (mg/100g)**

Lycopene, the pigment responsible for the red colour of tomatoes, is a powerful antioxidant linked to reduced risk of chronic diseases such as cardiovascular disorders and various epithelial cancers. Based on the data in Table 10, fertilizer dose, spacing, and variety had significant effects on lycopene content. The interaction effects of fertilizer dose × spacing and spacing × variety were also significant, while the fertilizer dose × variety interaction was not. The three-way interaction (fertilizer dose × spacing × variety) was found to be statistically significant as well.

Among the fertilizer treatments, F₂ produced the highest lycopene content (4.28 mg/100g), followed by F₁ (2.97 mg) and F₃ (2.56 mg). Regarding spacing, S₂ yielded the highest lycopene level (3.76 mg), which was significantly better than S₃ (3.07 mg) and S₁ (2.97 mg). Among the varieties, V₃ had the highest lycopene content (3.52 mg), followed by V₁ (3.34 mg) and V₂ (2.94 mg).

In the fertilizer dose × spacing interaction (Table 13), the maximum lycopene content (5.08 mg) was observed in F₂S₂, which was significantly superior to all other combinations. For the spacing × variety interaction (Table 13), the highest value (4.29 mg) was recorded in S₁V₃, which significantly outperformed all other spacing × variety treatments.

The three-way interaction (Table 17) showed lycopene content ranging from 1.51 mg (F₁S₁V₂) to 5.47 mg (F₂S₂V₂). The highest lycopene content recorded in F₂S₂V₂ was significantly superior to all other treatments.

These findings align with the studies of Bilalis et al. (2018) and Caralampides (2012), who reported that fertilizer dose significantly affects lycopene accumulation. Ilupeju et al. (2015) also confirmed the combined influence of fertilizer and varietal differences on lycopene content in tomato.

**Table 13. Interaction effect of fertilizer doses with spacing and spacing with varieties for lycopene content in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Lycopene content (mg/100g)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 2.50 | 3.85 | 2.56 | S1 | 2.56 | 2.08 | 4.29 |
| F2 | 3.51 | 5.08 | 4.23 | S2 | 4.09 | 3.73 | 3.44 |
| F3 | 2.91 | 2.34 | 2.42 | S3 | 3.38 | 3.01 | 2.83 |
| CD (P=0.05) |  | FS (1) | FS (2) | CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.06 | 0.05 |  |  | 0.05 | 0.05 |

F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

**Titratable acidity (%)**

Titratable acidity is a crucial quality parameter for processing tomatoes, as it contributes to the overall flavor and enhances the taste of tomato-based products. The data in Table 10 indicated that fertilizer dose had a significant effect on titratable acidity, while spacing and variety did not show any statistically significant influence. Among the interaction effects, fertilizer dose × spacing and spacing × variety were significant, whereas fertilizer dose × variety was not. The three-way interaction among fertilizer dose × spacing × variety also showed significant differences.

Among fertilizer treatments, the highest titratable acidity (0.307%) was recorded in F₃, followed by F₂ (0.287%) and F₁ (0.267%). Stress from competition or restricted resources (such as closer spacing) can result in an increase in acid accumulation as part of the stress response. For spacing, S₂ exhibited the highest acidity (0.297%), followed by S₃ (0.290%) and S₁ (0.273%). Among the varieties, V₃ had the highest titratable acidity (0.290%), which was statistically at par with V₂ (0.286%). In the fertilizer dose × spacing interaction (Table 14), the highest acidity (0.336%) was observed in F₃S₂, statistically at par with F₂S₁ (0.332%). The lowest titratable acidity value (0.198%) was found in F₁S₁. For the spacing × variety interaction (Table 14), the highest titratable acidity (0.369%) was recorded in S₃V₁, significantly superior to all other spacing × variety combinations. The lowest titratable acidity (0.212%) was noted in S₃V₃. The three-way interaction (Table 17) revealed that titratable acidity ranged from 0.147% (F₁S₂V₁) to 0.397% (F₃S₂V₂). The highest value observed in F₃S₂V₂ was statistically at par with F₃S₃V₁ (0.393%).

These results are consistent with the findings of Fandi et al. (2010), Laxmi et al. (2015), and Bilalis et al. (2018), who also reported a significant influence of fertilizer application on titratable acidity in tomato.

**Table 14. Interaction effect of fertilizer doses with spacing and spacing with varieties for titrable acidity in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Titrable acidity (%)** | | | | | | | |
| Fertilizer dose | Spacing | | | Spacing | Variety | | |
| S1 | S2 | S3 | V1 | V2 | V3 |
| F1 | 0.198 | 0.297 | 0.306 | S1 | 0.251 | 0.249 | 0.320 |
| F2 | 0.332 | 0.259 | 0.270 | S2 | 0.234 | 0.319 | 0.338 |
| F3 | 0.290 | 0.336 | 0.295 | S3 | 0.369 | 0.291 | 0.212 |
| CD(P=0.05) |  | FS (1) | FS (2) | CD(P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.007 | 0.007 |  |  | 0.01 | 0.01 |

F\*S(1)- CD for fertilizer doses measures at same spacing and F\*S(2)- CD for spacings at same or different fertilizer doses, S\*V(1)- CD for spacings measures at same varieties and S\*V(2)- CD for varieties at same or different spacings.

**Ascorbic acid (mg/100g)**

Ascorbic acid, also known as vitamin C, is a vital phytonutrient for human health and plays important roles in plant growth and development. Based on the data in Table 10, plant spacing and variety significantly influenced ascorbic acid content in tomato fruits, while fertilizer dose had no significant effect. Among interaction effects, spacing × variety was significant, whereas both fertilizer dose × spacing and fertilizer dose × variety were non-significant. However, the three-way interaction of fertilizer dose × spacing × variety was found to be statistically significant.

Among the spacing treatments, S₁ recorded the highest ascorbic acid content (14.1 mg/100g), followed by S₂ (13.6 mg) and S₃ (12.9 mg). Closer spacing can change the microenvironment surrounding the plant. It may result in higher humidity and a warmer canopy. These changes can influence enzyme activity related to ascorbate metabolism, resulting in increased ascorbic acid synthesis in some genotypes Regarding varieties, V₁ had the highest ascorbic acid level (14.0 mg), followed by V₂ (13.5 mg) and V₃ (13.1 mg).

**Table 15. Interaction effect of spacing with varieties for ascorbic acid in tomato**

|  |  |  |  |
| --- | --- | --- | --- |
| **Ascorbic acid (mg/100 g)** | | | |
| Spacing | Variety | | |
| V1 | V2 | V3 |
| S1 | 15.5 | 13.2 | 13.6 |
| S2 | 14.0 | 14.4 | 12.5 |
| S3 | 12.5 | 13.0 | 13.3 |
| CD (P=0.05) |  | SV (1) | SV (2) |
|  |  | 0.4 | 0.5 |

S- Spacings: S1- 45×45cm, S2- 60×45cm, S3- 75×45cm; V- Varieties: V1- DPT-1, V2-DPT-2, V3- Palam Pink; S\*V (1)- CD for spacings measures at same varieties and S\*V (2)- CD for varieties at same or different spacings.

The interaction between spacing and variety (Table 15) showed that the maximum ascorbic acid (15.5 mg) was observed in S₁V₁, which was significantly superior to all other combinations. The lowest values (12.5 mg) were recorded in S₃V₁ and S₂V₃.

The three-way interaction (Table 17) revealed a range of ascorbic acid values from 11.3 to 17.2 mg/100g. The highest content was observed in F₃S₁V₁, which was significantly superior to all other treatments.

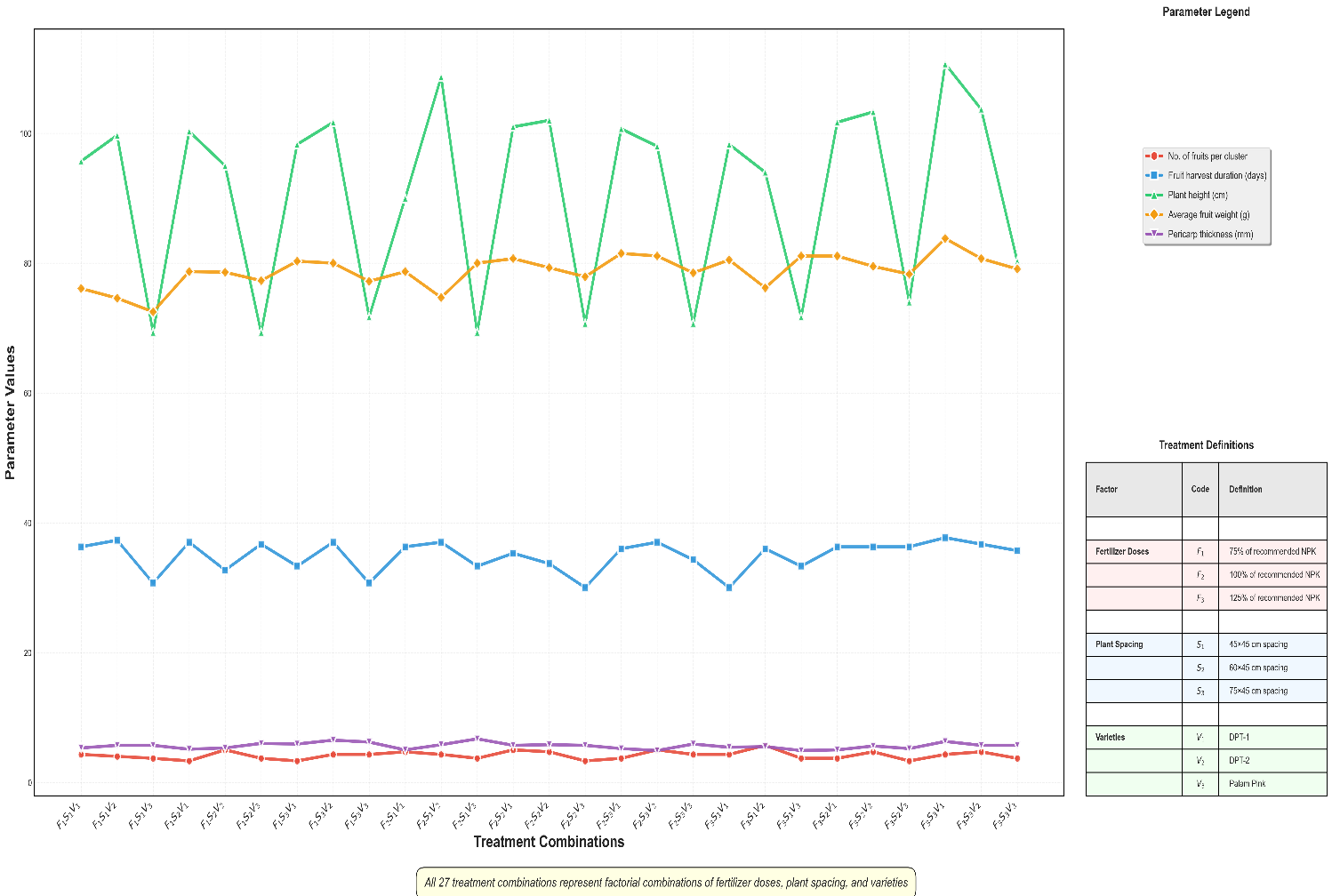
****These findings are in close agreement with those of Ilupeju et al. (2015), who reported a significant effect of variety on ascorbic acid concentration in tomato. However, they contrast with the results of Ogundare et al. (2015), who found no significant impact of spacing on acid content.

Fig. 1 Effect of fertilizer dose, spacing and variety on growth parameters under different treatment combinations

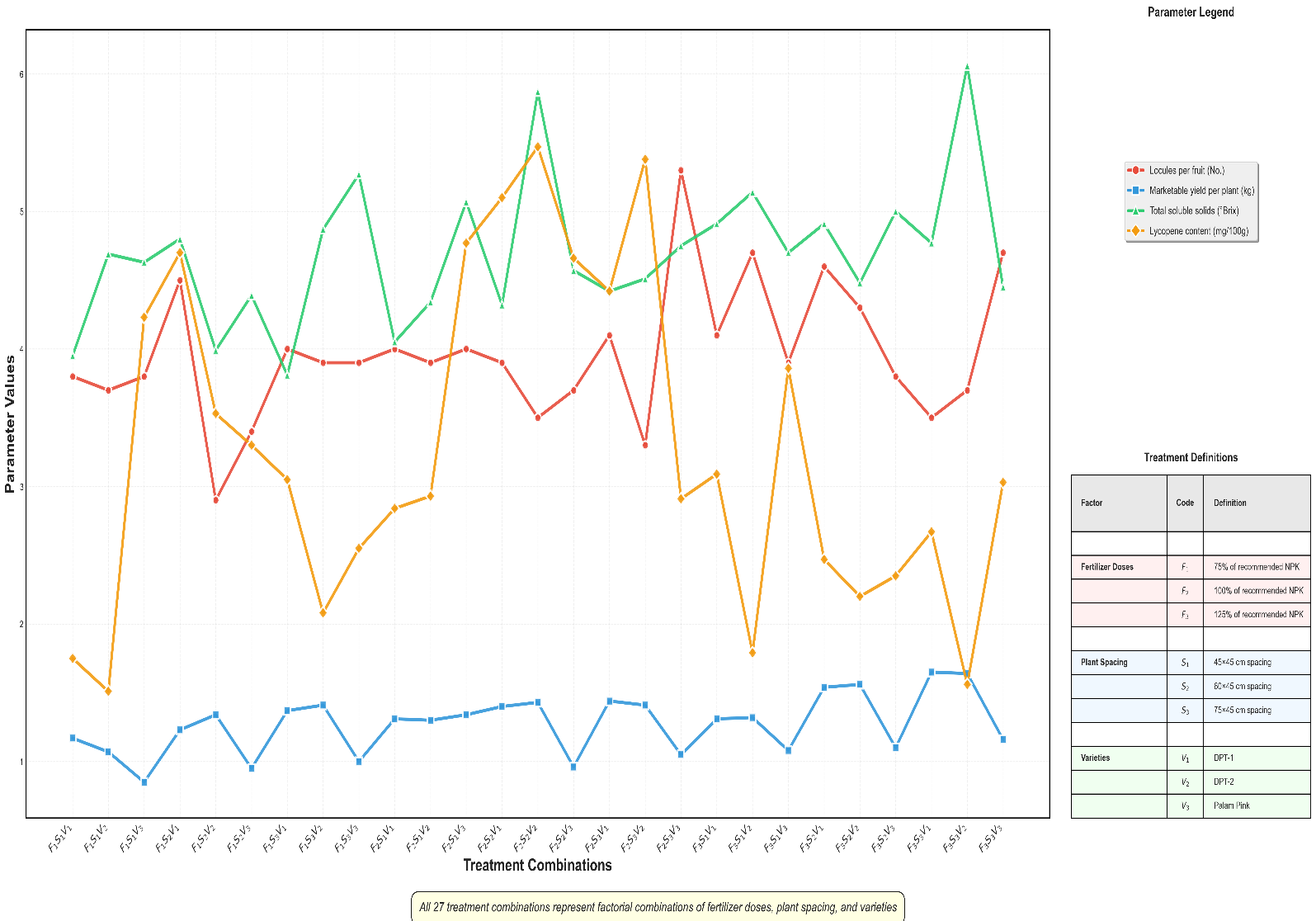
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Fig. 2 Effect of fertilizer dose, spacing and variety on growth and quality parameters under different treatment combinations

**Table 16. Interaction effect among fertilizer doses, spacing and varieties for different traits in tomato**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Sr. No** | **Treatment** | **Days to 50 per cent flowering** | **Days to first harvest** | **No. of fruits per cluster** | **Fruit harvest duration (days)** | **Plant height (cm)** | **Average fruit weight (g)** | **Pericarp thickness (mm)** |
| 1 | F1S1V1 | 24.3 | 74.0 | 4.3 | 36.3 | 95.7 | 76.1 | 5.3 |
| 2 | F1S1V2 | 26.7 | 72.7 | 4.0 | 37.3 | 99.7 | 74.6 | 5.7 |
| 3 | F1S1V3 | 24.0 | 72.7 | 3.7 | 30.7 | 69.3 | 72.5 | 5.7 |
| 4 | F1S2V1 | 25.0 | 73.3 | 3.3 | 37.0 | 100.3 | 78.7 | 5.1 |
| 5 | F1S2V2 | 27.3 | 75.0 | 5.0 | 32.7 | 95.0 | 78.6 | 5.3 |
| 6 | F1S2V3 | 24.3 | 72.0 | 3.7 | 36.7 | 69.3 | 77.3 | 6.0 |
| 7 | F1S3V1 | 25.3 | 73.3 | 3.3 | 33.3 | 98.3 | 80.3 | 5.9 |
| 8 | F1S3V2 | 28.0 | 73.0 | 4.3 | 37.0 | 101.7 | 80.0 | 6.5 |
| 9 | F1S3V3 | 26.7 | 71.3 | 4.3 | 30.7 | 71.7 | 77.2 | 6.2 |
| 10 | F2S1V1 | 23.0 | 71.7 | 4.7 | 36.3 | 90.0 | 78.7 | 5.0 |
| 11 | F2S1V2 | 28.0 | 73.7 | 4.3 | 37.0 | 108.7 | 74.7 | 5.8 |
| 12 | F2S1V3 | 24.0 | 71.0 | 3.7 | 33.3 | 69.3 | 80.0 | 6.7 |
| 13 | F2S2V1 | 26.0 | 76.7 | 5.0 | 35.3 | 101.0 | 80.7 | 5.7 |
| 14 | F2S2V2 | 29.3 | 73.0 | 4.7 | 33.7 | 102.0 | 79.3 | 5.8 |
| 15 | F2S2V3 | 26.0 | 72.0 | 3.3 | 30.0 | 70.7 | 77.9 | 5.7 |
| 16 | F2S3V1 | 26.0 | 74.0 | 3.7 | 36.0 | 100.7 | 81.5 | 5.2 |
| 17 | F2S3V2 | 27.0 | 77.0 | 5.0 | 37.0 | 98.0 | 81.1 | 4.9 |
| 18 | F2S3V3 | 25.0 | 73.0 | 4.3 | 34.3 | 70.7 | 78.5 | 5.9 |
| 19 | F3S1V1 | 27.3 | 75.3 | 4.3 | 30.0 | 98.3 | 80.5 | 5.4 |
| 20 | F3S1V2 | 27.0 | 73.0 | 5.7 | 36.0 | 94.0 | 76.2 | 5.5 |
| 21 | F3S1V3 | 27.7 | 71.3 | 3.7 | 33.3 | 71.7 | 81.1 | 4.9 |
| 22 | F3S2V1 | 29.7 | 73.0 | 3.7 | 36.3 | 101.7 | 81.1 | 5.0 |
| 23 | F3S2V2 | 25.0 | 73.3 | 4.7 | 36.3 | 103.3 | 79.5 | 5.6 |
| 24 | F3S2V3 | 26.7 | 75.0 | 3.3 | 36.3 | 74.0 | 78.3 | 5.2 |
| 25 | F3S3V1 | 26.7 | 75.3 | 4.3 | 37.7 | 110.7 | 83.8 | 6.3 |
| 26 | F3S3V2 | 29.7 | 74.7 | 4.7 | 36.7 | 103.7 | 80.7 | 5.7 |
| 27 | F3S3V3 | 26.3 | 75.0 | 3.7 | 35.7 | 80.3 | 79.1 | 5.7 |
| 28 | CD (5 %) | 2.0 | 2.7 | 1.0 | 3.1 | 7.2 | 2.4 | 0.7 |

**Table 17. Interaction effect among fertilizer doses, spacing and varieties for different traits in tomato**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Sr. No** | **Treatment** | **Locules per fruit (No.)** | **Marketable yield per plant (kg)** | **Total soluble solids (°Brix)** | **Lycopene content**  **(mg/100g)** | **Titrable acidity (%)** | **Ascorbic acid**  **(mg/100g)** |
| 1 | F1S1V1 | 3.8 | 1.17 | 3.95 | 1.75 | 0.167 | 14.4 |
| 2 | F1S1V2 | 3.7 | 1.07 | 4.69 | 1.51 | 0.183 | 12.5 |
| 3 | F1S1V3 | 3.8 | 0.85 | 4.63 | 4.23 | 0.243 | 14.7 |
| 4 | F1S2V1 | 4.5 | 1.23 | 4.80 | 4.70 | 0.147 | 15.2 |
| 5 | F1S2V2 | 2.9 | 1.34 | 3.99 | 3.53 | 0.384 | 13.9 |
| 6 | F1S2V3 | 3.4 | 0.95 | 4.39 | 3.30 | 0.360 | 12.8 |
| 7 | F1S3V1 | 4.0 | 1.37 | 3.81 | 3.05 | 0.334 | 14.6 |
| 8 | F1S3V2 | 3.9 | 1.41 | 4.87 | 2.08 | 0.380 | 11.6 |
| 9 | F1S3V3 | 3.9 | 1.00 | 5.27 | 2.55 | 0. 205 | 13.7 |
| 10 | F2S1V1 | 4.0 | 1.31 | 4.05 | 2.84 | 0.295 | 14.8 |
| 11 | F2S1V2 | 3.9 | 1.30 | 4.34 | 2.93 | 0.367 | 14.0 |
| 12 | F2S1V3 | 4.0 | 1.34 | 5.07 | 4.77 | 0.333 | 13.1 |
| 13 | F2S2V1 | 3.9 | 1.40 | 4.32 | 5.10 | 0.313 | 13.4 |
| 14 | F2S2V2 | 3.5 | 1.43 | 5.87 | 5.47 | 0.176 | 15.3 |
| 15 | F2S2V3 | 3.7 | 0.96 | 4.57 | 4.66 | 0.286 | 11.3 |
| 16 | F2S3V1 | 4.1 | 1.44 | 4.42 | 4.42 | 0.379 | 11.4 |
| 17 | F2S3V2 | 3.3 | 1.41 | 4.51 | 5.38 | 0.194 | 12.7 |
| 18 | F2S3V3 | 5.3 | 1.05 | 4.75 | 2.91 | 0.237 | 12.5 |
| 19 | F3S1V1 | 4.1 | 1.31 | 4.91 | 3.09 | 0.291 | 17.2 |
| 20 | F3S1V2 | 4.7 | 1.32 | 5.14 | 1.79 | 0.196 | 13.3 |
| 21 | F3S1V3 | 3.9 | 1.08 | 4.70 | 3.86 | 0.383 | 12.9 |
| 22 | F3S2V1 | 4.6 | 1.54 | 4.91 | 2.47 | 0.243 | 13.5 |
| 23 | F3S2V2 | 4.3 | 1.56 | 4.48 | 2.20 | 0.397 | 14.0 |
| 24 | F3S2V3 | 3.8 | 1.10 | 5.00 | 2.35 | 0.367 | 13.3 |
| 25 | F3S3V1 | 3.5 | 1.65 | 4.77 | 2.67 | 0.393 | 11.7 |
| 26 | F3S3V2 | 3.7 | 1.64 | 6.06 | 1.56 | 0.299 | 14.6 |
| 27 | F3S3V3 | 4.7 | 1.16 | 4.45 | 3.03 | 0.193 | 13.6 |
| 28 | CD (5%) | 0.7 | 0.11 | 0.30 | 0.08 | 0.011 | 0.7 |

**Conclusion**

Both the newly developed bacterial wilt resistant lines i.e., DPT-1 and DPT-2 gave the maximum marketable fruit yield per plant with the application of 125 per cent recommended dose of fertilizer at either recommended (60 × 45 cm) or wider (75 × 45 cm) spacing. Among the treatment combinations, F₃S₃V₁ (125% NPK, 75×45 cm spacing, DPT 1) was found to be most effective in improving marketable yield per plant, while F₂S₂V₂ and F₃S₁V₁ were found superior for lycopene and ascorbic acid content, respectively. These results demonstrate that integrating appropriate nutrient management with precise plant spacing can considerably improve the productivity and quality of tomato crops, particularly under conditions prone to bacterial wilt disease. The findings serve as a practical framework for formulating crop-specific agronomic strategies and selecting resilient cultivars to meet the dual goals of yield enhancement and nutritional improvement in tomato cultivation.

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Details of the AI usage are given below:

ChatGPT, GPT-4, developed by OpenAI, was used for paraphrasing and language refinement of portions of the manuscript.

The AI was not used for generating scientific content, data interpretation, or experimental conclusions.

Example prompt: "Paraphrase the following paragraph for clarity while retaining scientific meaning."

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