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NPK Fertilization Modulates Morphophysiological Responses, Yield, Fruit Quality, and Mineral Composition of *Solanum lycopersicum* L.

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Abstract

NPK fertilization can modify crop yield and contribute to the production of foods with greater nutritional value. However, further studies are needed to understand how different NPK rates modulate the responses of *Solanum lycopersicum*, particularly regarding fruit quality. Therefore, this study evaluated the effects of different NPK fertilization rates on the morphophysiological traits and yield of *S. lycopersicum* L. plants, as well as fruit quality based on physicochemical attributes, antioxidant activity, and mineral composition. The experiment was conducted under a completely randomized design with five treatments: T1 (700 kg ha^{-1}), T2 (1000 kg ha^{-1}), T3 (1500 kg ha^{-1}), T4 (2000 kg ha^{-1}), and T5 (2500 kg ha^{-1}). The results showed that T3 exhibited the most favorable performance in morphological variables, with a plant height of 154.61 cm, a leaf area of 20.1 cm^2, and 3.86 inflorescences per plant. This treatment also achieved the highest yield, with a total tomato production of 1.58 kg per plant and an estimated productivity of 52,666.7 kg ha^{-1} (52.67 t ha^{-1}). Regarding stomatal characteristics, T3 presented 23.33 stomata and a stomatal density of 106.1, according to the corresponding measurement units. Concerning fruit physicochemical quality, T3 exhibited a balanced profile of physicochemical attributes and antioxidant activity, with intermediate values for total soluble solids (6.13 °Brix), total soluble sugars (4.32%), and antioxidant capacity assessed using the ferric reducing antioxidant power (FRAP) assay (23.6%). Regarding mineral composition, fruits from plants subjected to T3 showed greater accumulation of calcium, potassium, and magnesium, with concentrations approximately 70–100 times higher than those in the control treatment. These results suggest that the NPK rate of 1500 kg ha^{-1} simultaneously favored plant growth, yield, and several attributes associated with fruit nutritional quality. In contrast, lower or higher rates were associated with less favorable responses in several evaluated variables. Overall, NPK rates differentially modulated plant growth, yield, and fruit nutritional quality, with T3 (1500 kg ha^{-1}) showing the most favorable overall performance.

Keywords: tomato; Río Grande variety; antioxidant activity; macronutrients; micronutrients

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1. Introduction

The increase in the world population in recent decades has generated a greater demand for food production [1], particularly for plant products with high nutritional value [2]. According to the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO), a daily consumption of at least 400 g of fruits and vegetables per person is recommended [3], as it helps prevent chronic diseases and promotes a healthy diet [2]. Given this situation, it is essential to ensure the production of crops that contribute to food security, as well as crops that provide nutritional properties beneficial to human health.

The tomato (*Solanum lycopersicum* L.), belonging to the Solanaceae family, is the second most cultivated vegetable worldwide after the potato [4]. From a nutritional perspective, it is an important source of minerals and bioactive compounds that contribute directly to human health [5]. The main minerals present in tomatoes include Iron (Fe), Magnesium (Mg), Zinc (Zn), Potassium (K), Calcium (Ca), Phosphorus (P), Manganese (Mn), and Copper (Cu) [6,7], as well as carotenoids, phenolic compounds, vitamins, and glycoalkaloids [8]. Among tomato cultivars, Río Grande stands out for its high agronomic yield, wide adaptation to climatic variations, and outstanding nutritional and antioxidant properties [9]. These characteristics make it one of the preferred cultivars for culinary uses and industrial processing [10]. According to Singh et al. [11], fertilization through the combined application of nitrogen (N), phosphorus (P), and potassium (K) promotes plant growth and yield in several crops. However, inadequate application of these nutrients may negatively affect crop production and directly impact farmers [1]. In this regard, balanced fertilization based on the appropriate and rational use of NPK not only improves crop productivity but may also enhance the nutritional value of fruits and contribute to the sustainability of agricultural systems [12,13].

In tomato cultivation, NPK application positively influences morphological traits by promoting improved plant development, particularly increased plant height, leaf production, and fruit yield [14,15]. At the physiological level, adequate NPK supply can improve processes related to chlorophyll synthesis, enzymatic activity, and gas exchange [16], thereby contributing to increased crop productivity [17]. However, the effects of different NPK application rates on fruit quality, particularly regarding physicochemical attributes, antioxidant capacity, and mineral composition, remain insufficiently explored, highlighting an important knowledge gap. Furthermore, in the context of increasing global food demand, determining appropriate NPK application rates could contribute not only to increased productivity but also to the production of fruits with higher concentrations of essential mineral elements for human nutrition. Although favorable effects of high NPK levels on tomato yield have been reported [14], crop responses depend on the amount of nutrients applied, and excessive fertilization does not necessarily guarantee proportional improvements in productive, physiological, or nutritional traits. Therefore, it can be hypothesized that balanced NPK fertilization may favorably modulate plant growth, physiological responses, yield, and fruit quality.

Understanding the response of tomato plants to different fertilization levels is therefore essential for optimizing crop nutritional management. In this context, the present study aimed to evaluate the effects of different NPK fertilization rates on the morphophysiological responses and yield of *Solanum lycopersicum* L. plants, as well as to determine their influence on physicochemical attributes, antioxidant activity, and mineral composition of the fruits. The findings provide relevant information for optimizing crop nutritional management and promoting the efficient and rational use of NPK fertilization in tomato production systems.

2. Materials and Methods

2.1. Area and Soil Characterization

The research was conducted in the district of Villa Rica, province of Oxapampa, department of Pasco, Peru (Figure 1A). The district is located at an altitude of 1500 m above sea level. The average annual temperature ranges between 18 and 25 °C, with a mean value of approximately 18.32 °C. Annual rainfall reaches 1500 mm, and relative humidity is high, fluctuating between 70, and 90%, with an average of 88.99% [18]. The experiment was conducted from 10 July to 17 November 2025.

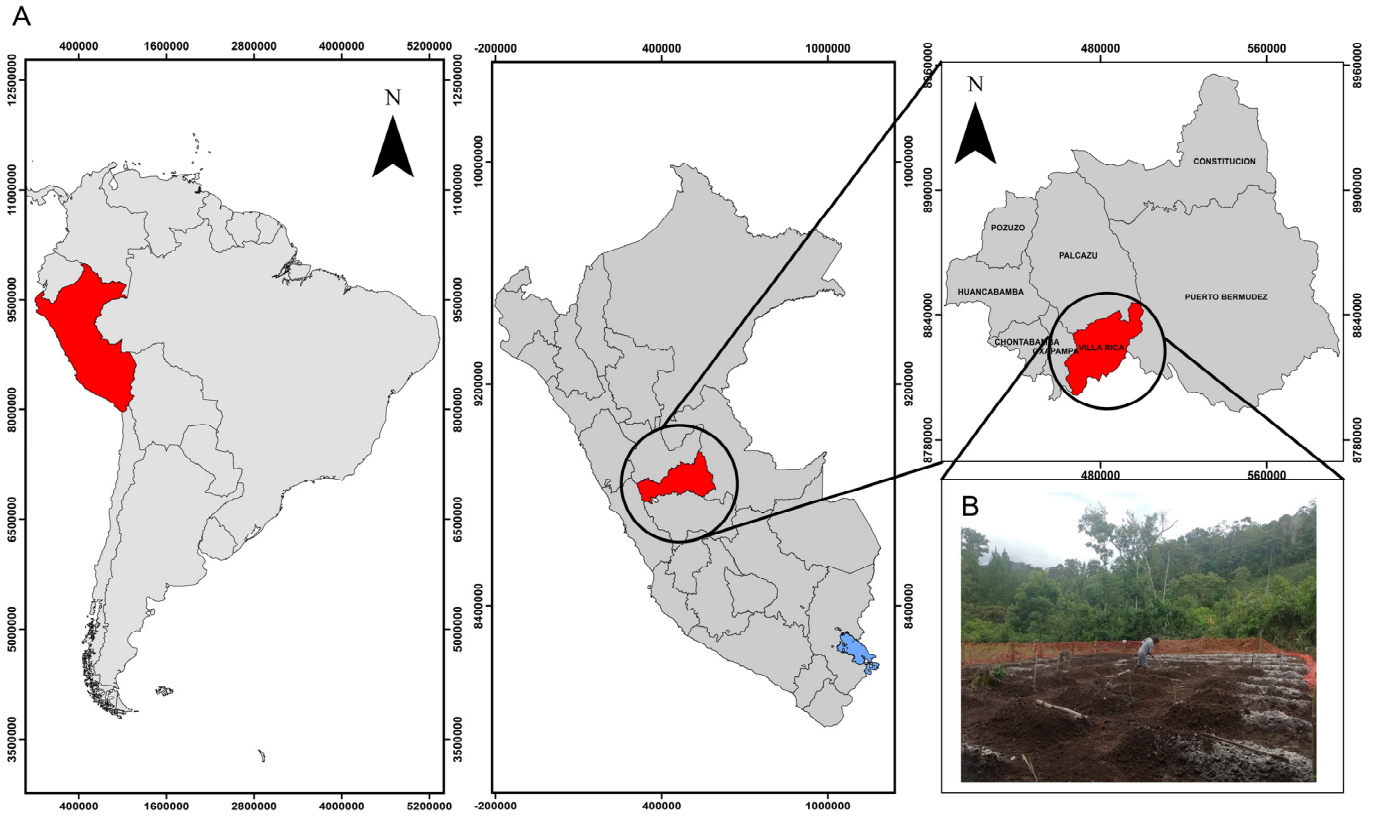


Figure 1. Geographic location of the district of Villa Rica, Pasco region, Peru (**A**). Soil pH adjustment with $CaCO_3$ (**B**).

For the establishment of the experiment, soil composition was analyzed. To this end, seven subsamples were randomly collected, homogenized, and subsequently analyzed for soil fertility. The soil characteristics were considered suitable for fertilization experiments, as they presented 5.16 meq 100 g^{-1} of sum of exchangeable cations (SEC) [19]. In addition, the soil texture was classified as loam, with a cation exchange capacity (CEC) of 12.16 and a pH of 4.98, indicating strongly acidic conditions (Table 1).

The soil characteristics showed a cation exchange capacity (CEC) of 12.16 meq 100 g^{-1}, classifying the soil as nutrient-poor [19]. In addition, the soil texture was classified as loam, and the pH was 4.98, indicating strongly acidic conditions (Table 1). Before the experiment was established, soil pH was corrected by liming. For this purpose, 1.04 tonnes ha^{-1} (40.56 kg over an area of 390 m^2) of $CaCO_3$ (agricultural lime) were applied to increase the pH from 5.5 to 6, a range considered suitable for tomato cultivation without affecting Mn and Zn availability [20] (Figure 1B).

Table 1. Soil characteristics of the experiment. EC: Electrical conductivity. CEC: Cation exchange capacity. Al^{3+} + H^{+}: Exchangeable acidity. SEC: Sum of Exchangeable Cations. $CaCO_3$: Calcium carbonate.

pH	E.C (dS m^{-1})	Organic Matter (%)	Silt (%)	Clay (%)	Sand (%)
4.98	0.13	6.65	48	11	41
CEC (meq 100 g^{-1})	**P (ppm)**	**K (ppm)**	**$CaCO_3$ (%)**	**Ca^{2+} (meq 100 g^{-1})**	**Mg^{2+} (meq 100 g^{-1})**
12.16	2.8	204	0.00	3.35	0.44
K^{+} (meq 100 g^{-1})	**Na^{+} (meq 100 g^{-1})**	**Al^{3+} + H^{+} (meq 100 g^{-1})**	**SEC (meq 100 g^{-1})**	**Total Bases**	**Base Saturation (%)**
0.56	0.80	0.80	5.16	4.36	36

2.2. Plant Material and Experimental Design

For plant material production, seeds of *Solanum lycopersicum* L. (tomato), Río Grande variety, were germinated. At 30 days after germination, seedlings with a height of 15–20 cm and three to four true leaves were selected. Subsequently, the plants were transplanted to the field at a spacing of 0.30 m between plants and 1.0 m between rows (Figure 2A–C). NPK fertilization was applied in split applications at different times after transplanting. Irrigation was not necessary because Villarrica experienced light rainfall during the experimental period. In addition, soil maintenance was performed every 15 days to prevent weed growth and avoid potential interference with the experiment.

The experiment was established under a completely randomized design (CRD), with 15 experimental plots, comprising three plots per treatment (three replicates per treatment). Each plot consisted of 48 plants arranged in an 8 × 6 configuration. To minimize border effects, only the 24 plants located in the central area of each plot were evaluated, while the peripheral plants were excluded from the evaluation (Figure 2D). Therefore, a total of 360 plants were evaluated.

The fertilization treatments consisted of five application rates of the commercial fertilizer YaraMila® COMPLEX™ (Imported and distributed by EQUILIBRA PERÚ S.A., Lima, Peru), containing 12.4% N, 11% P_2O_5, and 18% K_2O. According to the manufacturer's recommendations, the application rate ranges from 300 to 500 kg ha^{-1} for soils with medium to high fertility. However, due to the low initial fertility of the soil used in this study, higher application rates were established to evaluate tomato responses to increasing levels of nutrient supply. The rate of 700 kg ha^{-1} (21 g $plant^{-1}$) was established as the reference treatment (T1), while treatments T2–T5 received progressively higher application rates of 1000 (30 g $plant^{-1}$), 1500 (45 g $plant^{-1}$), 2000 (60 g $plant^{-1}$), and 2500 kg ha^{-1} (75 g $plant^{-1}$), respectively. The total fertilizer rate for each treatment was split into three applications: 20% at 15 days after transplanting (DAT), 40% at 40 DAT, and 40% at 70 DAT. All treatments were subjected to the same agronomic management practices. Morphological and physiological traits, yield-related parameters, fruit quality attributes, and mineral element composition were subsequently evaluated. The fertilizer rates applied and the corresponding amounts of N, P_2O_5, and K_2O for each treatment are presented in Table 2, while the experimental scheme is illustrated in Figure 2D.

Table 2. Fertilization treatments and corresponding nutrient application rates.

Tra	Fertilizer Rate (kg ha^{-1})	Fertilizer Rate (g plant^{-1})	Relative to RDF	N (kg ha^{-1})	P_2O_5 (kg ha^{-1})	K_2O (kg ha^{-1})
T1 (RDF)	700	21	1.00×	86.8	77	126
T2	1000	30	1.43×	124	110	180
T3	1500	45	2.14×	186	165	270
T4	2000	60	2.86×	248	220	360
T5	2500	75	3.57×	310	275	450

Tra: Treatment. RDF: recommended dose of fertilizer per product YaraMila® COMPLEX.



Figure 2. Crop establishment and experimental design of NPK fertilization. (**A**) Germination of tomato seeds. (**B**) Transplanting to the final field. (**C**) Application of YaraMila® fertilizer. (**D**) Experimental design and post-transplanting NPK application.

2.3. Analysis of Morphophysiological and Yield Parameters

For the morphological analysis, different variables were evaluated at 20, 50, 70, and 90 days after transplanting. Plant height (PH), Base diameter of the plant (BDP), leaf area (LA), number of inflorescences (Ninf), and number of flower buds (NFB) were assessed (Figure 3A).



Figure 3. Agronomic evaluation and phenological phases of the crop. (**A**) Measurement of seedlings. (**B**) Start of flowering (50 days after transplanting). (**C**) Start of fruit ripening. (**D**) Ripe fruits.

To estimate leaf area (LA), the methodology proposed by Lyon [21] was used, applying the following Equation (1):

$$LA = 0.1551 \times (LH)^2 \quad (1)$$

where *LH*: leaf length.

At 60 and 70 days after transplanting, the plants entered the flowering and fruiting stages, and additional variables were evaluated, including the number of flowers (NFl) and number of fruits (NFr) (Figure 3B,C).

Tomato fruit yield (TY) was also evaluated. For this purpose, fruits were harvested on two occasions (70 and 90 days after transplanting) when they reached full ripeness (red color) (Figure 3D). Yield was determined based on fruit mass per plant (kg plant^{-1}) and subsequently extrapolated to kilograms per hectare (kg ha^{-1}). The following Equation (2) was used to calculate fruit yield (kg ha^{-1}):

$$Yield\left(\text{kgha}^{-1}\right) = \frac{plants}{ha} \times \frac{kg\ of\ fruit}{plant} \quad (2)$$

where plants ha^{-1}: planting density. kg of fruit/plant: average fruit mass.

Tomato yield was visualized using a second-order polynomial regression and quantified using the coefficient of determination (R^2). Additionally, a three-dimensional response surface analysis was performed to evaluate the relationships among plant height (PH), leaf area (LA), and tomato yield (TY) under the different fertilizer rates applied. For this purpose, a second-order polynomial regression model was fitted, including the linear and quadratic effects of plant height and leaf area, as well as the interaction between both variables. The generated surfaces allowed visualization of the combined effects of PH and LA on the predicted TY values, represented by surface elevation and color gradients. The goodness of fit of the model was evaluated using the coefficient of determination (R^2), while the statistical significance of the regression was determined based on the corresponding *p*-value. All statistical analyses and graphical representations were performed using R software, version 4.6.1.

To evaluate the effects of different NPK rates on plant physiology, stomatal number and stomatal density (number of stomata per mm^2) were assessed. For this purpose, 50 days after transplanting, leaflets (three per treatment) were collected from the fourth and sixth

leaves of the petiole. The sampled leaf corresponded to the fourth leaf from the node of the seedlings.

The collected leaflets were immediately immersed in 70% ethanol for 5 min. Subsequently, a separation cut was performed to obtain the abaxial epidermis. A 1 cm^2 tissue section was placed on a microscope slide, and Lugol's iodine solution was applied to stain the stomata within the epidermal tissue. Stomata were visualized and quantified using an optical microscope with a field of view of 0.22 mm^2 at 40× magnification [22].

2.4. Analysis of Solanum lycopersicum L. Fruit Quality Based on Physicochemical Attributes and Antioxidant Capacity

Tomato fruit quality was evaluated based on physicochemical attributes and antioxidant capacity. The physicochemical attributes assessed included total soluble solids (TSSo), total soluble sugars (TSSu), titratable acidity (TA), and the sugar-to-acid ratio (SAR). For all analyses, five ripe fruits per treatment were used, collected 70 days after transplanting.

Total soluble solids (TSSo) were determined using 50 µL of tomato juice per treatment, and readings were obtained with a THE01505® manual optical refractometer (Shenzhen Yago Technology Limited, Guangdong, China) with automatic temperature compensation, operating within a range of 0 to 90 °Brix [7].

Total soluble sugars (TSSu) were calculated using the following Equation (3) proposed by Jing [23]:

$$TSSu\ (\%) = (TSSo \times 0.7082) \quad (3)$$

where *TSSo*: Total soluble solids.

Titratable acidity (TA) was determined by titration following the methodology described by Felföldi et al. [24]. For this purpose, 20 g of tomato fruit were homogenized with 20 mL of distilled water. The homogenate was then filtered and titrated with a 0.1 N NaOH solution in the presence of phenolphthalein as an indicator. Total acidity was calculated using the following Equation (4):

$$TA\ (\%) = V \times N \times 0.064 \times \frac{100}{m} \quad (4)$$

where *TA*: titratable acidity (% citric acid); *V*: volume of NaOH solution used in the titration (mL); *N*: concentration of the 0.1 N NaOH solution; 0.064 equivalent gram of citric acid; and m: mass of the sample (g).

To determine the sugar-acid ratio (SAR), the methodology described by He et al. [2] was applied, using the following Equation (5):

$$SAR = \frac{TSSu}{TA} \quad (5)$$

where *TSSu*: Total soluble sugars, and *TA*: Titratable acidity. The sugar-to-acid ratio (SAR) was visualized using a second-order polynomial regression, and the goodness of fit of the model was evaluated using the coefficient of determination (R^2) [25]. Additionally, a three-dimensional response surface analysis was performed to evaluate the relationships among plant height (PH), leaf area (LA), and the sugar-to-acid ratio (SAR), following the same parameters and statistical procedures previously described for the response surface analysis of tomato yield.

The antioxidant capacity of tomato fruits was determined spectrophotometrically (Hanna Instruments®, Woonsocket, RI, USA) using the ferric reducing antioxidant power (FRAP, Sigma-Aldrich®, Based in Darmstadt, Germany) assay. For this analysis, four ripe fruits per treatment were used, following the methodology described by [26]. For extract preparation, 0.5 g of tomato sample was mixed with 5 mL of methanol. The mixture was continuously agitated for 20 min and subsequently centrifuged at 10,000× *g* for 15 min

at 4 °C. The resulting supernatant was collected, while the residue was subjected to a second extraction by adding 4 mL of hexane for 30 min. Subsequently, the mixture was homogenized and centrifuged again under the same conditions described above. The resulting supernatants were collected and immediately frozen until further analysis. To determine antioxidant capacity using the FRAP assay, 30 µL of the tomato extract was mixed with 1 mL of FRAP reagent. The mixture was incubated at 37 °C for 4 min, after which absorbance was measured at 593 nm using water as the blank. Quantification was performed using a calibration curve ranging from 0 to 1000 µmol L^{-1} of ferrous ions, prepared with freshly prepared ferrous ammonium sulfate daily [27,28].

2.5. Analysis of the Composition of Solanum lycopersicum L. Fruits

For the analysis of mineral composition, fully ripe fruits were dried in an oven at 105 °C for 48 h. Subsequently, 0.5 g of dry material was weighed for digestion. Minerals were extracted by acid digestion, first with hydrochloric acid (HCl) at a 1:1 ratio, followed by digestion with nitric acid (HNO_3). After cooling, the digestate was transferred to a 50 mL volumetric flask [29]. The resulting solutions were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES) using a PerkinElmer AVIO® 500 instrument (PerkinElmer, MA, USA).

All mineral elements were classified as micronutrients and macronutrients, and were quantified in mg Kg^{-1}. In addition, mineral variation was evaluated by comparing T1 with the other treatments. The percentage variation (%) was calculated using the following Equation (6):

$$Variation\ (\%) = \frac{V_f - V_i}{V_i} \times 100 \quad (6)$$

where V_f is the mineral content obtained from any treatment (T2, T3, T4, or T5), and V_i is the mineral content obtained from the control treatment (T1).

2.6. Data Analysis

All data obtained from the evaluated variables were tested for normality and homoscedasticity assumptions. Normality was assessed using the Shapiro–Wilk test, while homoscedasticity was evaluated using Levene's test. Data that met these assumptions were subjected to analysis of variance (ANOVA), and mean comparisons were performed using Tukey's test at a significance level of $p \leq 0.05$. When the assumptions of normality and homoscedasticity were not satisfied, the data were analyzed using the nonparametric Kruskal–Wallis test.

Linear regression models were applied to physiological parameters, whereas polynomial regression models were used for yield-related parameters [25]. In addition, multivariate analyses were conducted. Principal component analysis (PCA) was performed using all evaluated variables, and graphical representation was generated with the ggplot2 package, incorporating confidence ellipses at a 95% confidence level in the biplot. Correlation analysis between variables was carried out using Spearman's correlation coefficient with the corrplot package, considering correlation values of $-0.6 \geq \rho \geq 0.6$ as strong correlations. All statistical analyses were performed using RStudio software, version 4.6.1.

3. Results

3.1. Effect of NPK on Morphophysiological and Yield Parameters

The morphophysiological and yield parameters of tomato plants showed significant differences among treatments for all evaluated variables ($p \leq 0.05$). Throughout the evaluation period, a pattern of progressive growth was observed for most morphological traits (Figure 4). During the evaluation period, plant height (PH), basal plant diameter (BDP),

and leaf area (LA) showed a progressive increase throughout the evaluation period, reflecting a gradual growth pattern of the plants (Figure 4A–C). At 20 days after transplanting (DAT), treatment T2 (124 kg N ha^{-1}, 110 kg P_2O_5 ha^{-1}, and 180 kg K_2O ha^{-1}) showed superior performance in plant height (PH) and basal stem diameter (BDP), reaching 52.46 cm and 8.37 mm, respectively. In contrast, leaf area (LA) was highest under treatment T3 (186 kg N ha^{-1}, 165 kg P_2O_5 ha^{-1}, and 270 kg K_2O ha^{-1}), reaching 20.18 cm^2.

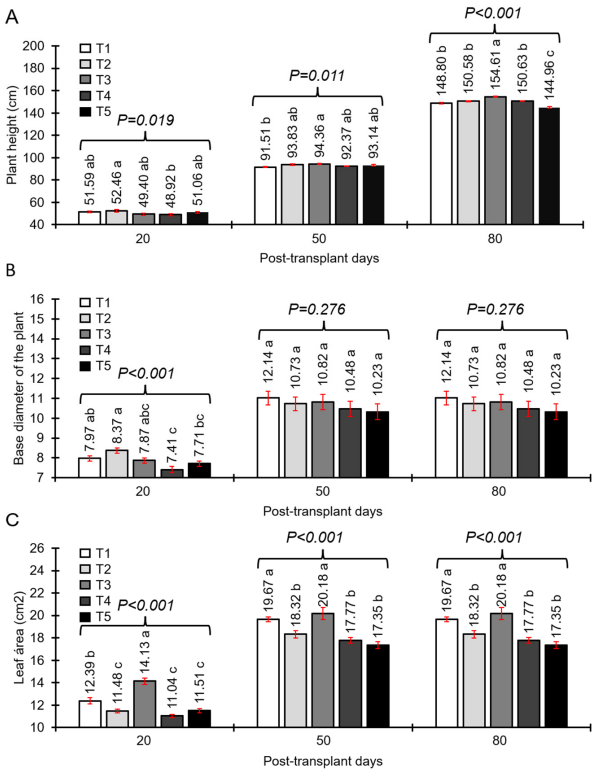


Figure 4. Morphological responses of tomato plants to different NPK fertilization rates. Different letters (a, b, and c) indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$).

At 50 and 80 DAT, PH and LA exhibited more pronounced differences among the treatments ($p < 0.001$) (Figure 4A,C). In particular, T3 consistently showed the best overall performance compared with the other NPK fertilization treatments, reaching 154.61 cm in PH and 20.10 cm^2 in LA. In contrast, BDP did not differ significantly among the NPK fertilization treatments ($p = 0.276$) (Figure 4B).

Regarding the reproductive traits, including the number of inflorescences (Ninf), flower buds (NFB), flowers (NFl), and fruits (NFr), significant differences were observed among treatments ($p \leq 0.05$) (Figure 5). For Ninf, at 20 days after transplanting (DAT), treatment T1 (86.8 kg N ha^{-1}, 77 kg P_2O_5 ha^{-1}, and 126 kg K_2O ha^{-1}) showed the highest value, with 1.92 inflorescences per plant. At 50 and 80 DAT, treatment T3 (186 kg N ha^{-1}, 165 kg P_2O_5 ha^{-1}, and 270 kg K_2O ha^{-1}) outperformed the other treatments, reaching 3.96 inflorescences per plant at 80 DAT (Figure 5A).

Flower bud production (NFB) was first observed at 35 DAT, with treatment T1 showing the highest values at this stage (Figure 5B). Regarding NFl, evaluated at 50 and 80 DAT, treatment T3 produced the highest number of flowers, with 10.17 and 9.39 flowers per plant, respectively (Figure 5C). For NFr, treatment T5 (2500 kg ha^{-1}; 310 kg N ha^{-1}, 275 kg P_2O_5 ha^{-1}, and 450 kg K_2O ha^{-1}) produced the highest number of fruits per plant (Figure 5D).

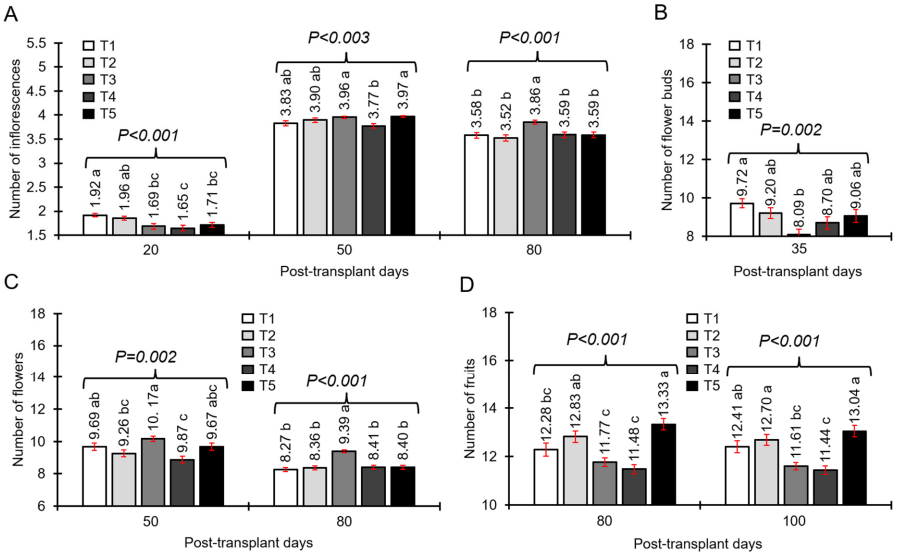


Figure 5. Reproductive responses of tomato plants to different NPK fertilization rates. Different letters (a, b, and c) indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$).

Regarding the physiological parameters, the number of stomata (NS) and stomatal density (SD) showed significant differences among treatments ($p < 0.001$) (Figure 6). Both variables exhibited a positive linear trend in response to increasing NPK fertilization rates, with coefficients of determination (R^2) of 0.96 and 0.97, respectively (Figure 6A,B). Treatments T4 and T5 recorded the highest NS values (24.33 and 24.60, respectively) and SD values (110.6 and 112.1, respectively). In contrast, treatment T1, corresponding to the lowest fertilization rate, presented the lowest NS (21.0) and SD (95.5) values. This trend was also evident in the graphical representation (Figure 6C), where the lowest number of stomata was observed in T1, whereas T5 exhibited the highest number of stomata (Figure 6D).

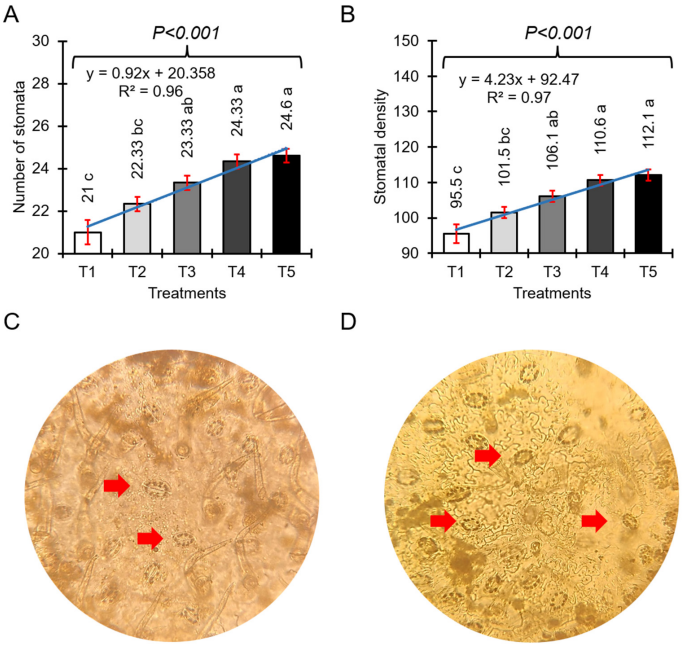


Figure 6. Physiological parameters. (**A**) stomatal number, (**B**) stomatal density, and representative images of stomatal number in treatments (**C**) T1 and (**D**) T5. Different letters (a, b, and c) indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$). The red arrows indicate the stomata on the tomato leaves.

Regarding tomato yield, the different NPK fertilization rates showed significant differences among treatments ($p < 0.001$) (Figure 7). The yield response to fertilization rates followed a second-order polynomial trend ($y = -0.0814x^2 + 0.4666x + 0.758$; $R^2 = 0.6704$), indicating an increase in yield up to an optimum point, followed by a decline at higher fertilizer rates. Treatment T3 exhibited the highest yield compared with the other treatments, reaching 1.58 kg per plant, equivalent to a total production of 37 kg per treatment and an estimated yield of 52,666.7 kg ha^{-1} (52.67 t ha^{-1}). In contrast, treatment T5 recorded the lowest values, with 1.07 kg per plant, a total production of 25 kg per treatment, and an estimated yield of 35,666.6 kg ha^{-1} (35.67 t ha^{-1}) (Figure 7A).

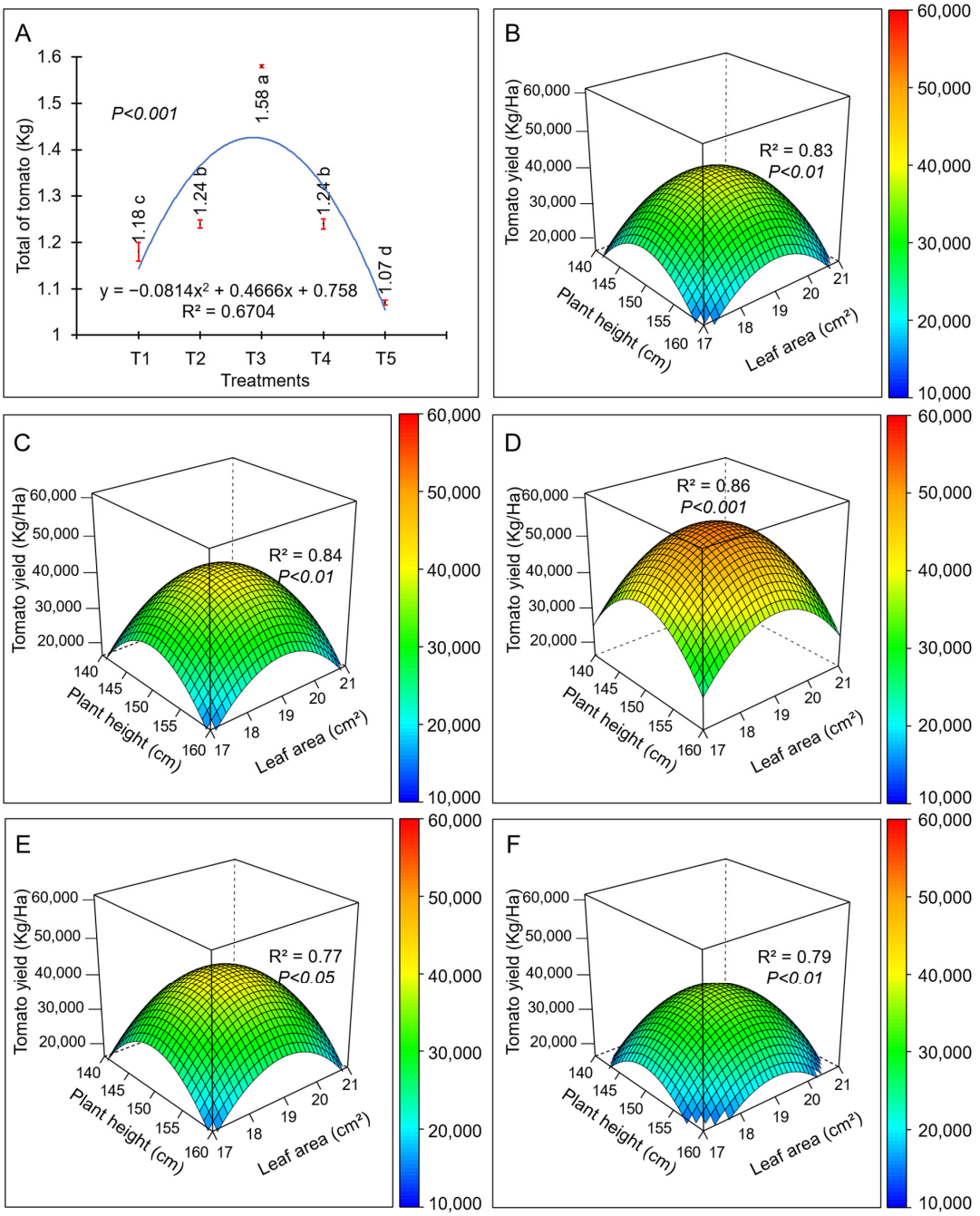


Figure 7. Tomato yield (**A**). Three-dimensional models of the interaction among plant height, leaf area, and tomato yield under different treatments (**B**–**F**). T1, T2, T3, T4 and T5 is 700, 1000, 1500, 2000 and 2500 kg ha^{-1}, respectively. Different letters (a, b, and c) indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$).

Furthermore, the three-dimensional response surface models (Figure 7B–F) revealed interactions among plant height, leaf area, and tomato yield. The models explained a considerable proportion of the observed variation, with coefficients of determination (R^2) ranging from 0.77 to 0.86, with statistical significance levels ranging from $p < 0.05$ to $p < 0.001$. Overall, the highest yield values were associated with specific ranges of vegetative growth, particularly plant heights between 145 and 155 cm and leaf areas between 18 and 20 cm^2. The best statistical fit and predictive performance among the multivariate regression models were obtained for the model presented in Figure 7D ($R^2 = 0.86$; $p < 0.001$). Additionally, treatment T3 produced fruits with larger morphological dimensions, indicating an increase in fruit size compared with the other treatments (Figure 8).

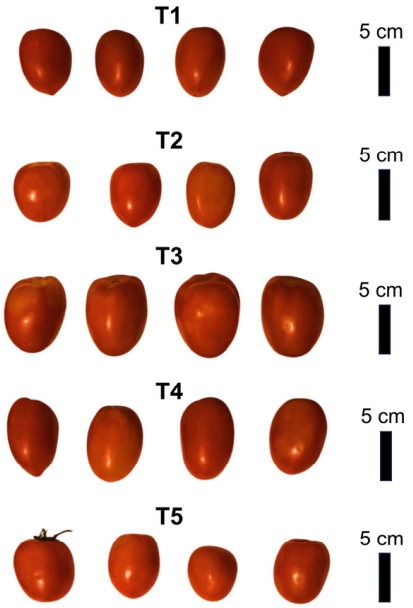


Figure 8. Morphological characteristics of tomato fruits in response to different NPK fertilization rates. T1, T2, T3, T4 and T5 is 700, 1000, 1500, 2000 and 2500 kg ha^{-1}, respectively.

3.2. Effect of NPK Fertilization on Tomato Fruit Quality Based on Physicochemical Attributes and Antioxidant Activity

The variables evaluated in relation to the physicochemical attributes and antioxidant capacity of the fruits showed significant differences among the NPK fertilization treatments ($p \leq 0.05$) (Table 3). Total soluble solids (TSSo) and total soluble sugars (TSSu) exhibited a decreasing trend as NPK fertilization rates increased. Treatment T1 (86.8 kg N ha^{-1}, 77 kg P_2O_5 ha^{-1}, and 126 kg K_2O ha^{-1}) recorded the highest values of TSSo (6.21 °Brix) and TSSu (4.39%). In contrast, treatment T5 (310 kg N ha^{-1}, 275 kg P_2O_5 ha^{-1}, and 450 kg K_2O ha^{-1}) presented the lowest values, with 5.83 °Brix for TSSo and 4.11% for TSSu.

Regarding titratable acidity (TA), a differential response was observed among treatments, reflecting variations in relation to sugar concentrations. Treatment T4 (248 kg N ha^{-1}, 220 kg P_2O_5 ha^{-1}, and 360 kg K_2O ha^{-1}) showed significantly higher values than T1 and T3. As a consequence of the variations observed in soluble solids and titratable acidity, the sugar-acid ratio (SAR) ranged from 9.72 to 12.91, with the highest value recorded in T1 (12.91) and the lowest in T4 (9.72). The relationship between soluble solids and titratable acidity was fitted to a second-order polynomial model ($R^2 = 0.7253$), indicating a nonlinear relationship between these variables (Figure S1A). In general, treatments with lower nutrient inputs, particularly T1, presented higher SAR values, associated with higher sugar concentrations and lower titratable acidity. In contrast, treatments receiving higher

fertilization rates, particularly T4 and T5, showed higher titratable acidity and lower soluble sugar concentrations, resulting in a reduction in SAR.

Table 3. Fruit quality analysis.

Tra	TSSo (°Brix)	TSSu (%)	TA (%)	SAR	FRAP (%)
T1	6.21 ± 0.08^{A}	4.39 ± 0.02^{A}	0.34 ± 0.03^{B}	12.91	21.85 ± 2.2^{B}
T2	6 ± 0.1^{BC}	4.25 ± 0.04^{AB}	0.38 ± 0.04^{AB}	11.18	23.34 ± 1.8^{AB}
T3	6.13 ± 0.07^{AB}	4.32 ± 0.08^{AB}	0.34 ± 0.05^{B}	12.71	23.62 ± 2.1^{AB}
T4	5.91 ± 0.1^{CD}	4.18 ± 0.03^{BC}	0.43 ± 0.04^{A}	9.72	25.64 ± 1.6^{A}
T5	5.83 ± 0.09^{D}	4.11 ± 0.02^{C}	0.4 ± 0.09^{AB}	10.28	26.23 ± 1.9^{A}
P	<0.001	<0.001	<0.01	-	<0.001

Tra: Treatment. TSSo: Total soluble solids (°Brix). TSSu: Total soluble sugars (%). TA: Titratable acidity (%). S-AR: Sugar-acid ratio. FRAP: Ferric reducing antioxidant power. Different letters (A, B, C and D) indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$).

Furthermore, the three-dimensional response surface models (Figure S1B–F) showed that SAR was influenced by the interaction between plant height and leaf area under the different fertilization levels. The models exhibited high and statistically significant coefficients of determination, with values ranging from $R^2 = 0.78$ ($p < 0.05$) to $R^2 = 0.89$ ($p < 0.001$). Overall, the highest SAR values were concentrated in plants with heights between 145 and 155 cm and leaf areas between 18 and 20 cm^2. The best statistical fit and predictive capacity were observed in the model corresponding to treatment T3 ($R^2 = 0.89$; $p < 0.001$) (Figure S1D), indicating that the simultaneous optimization of vegetative growth, particularly plant height and leaf area, was associated with a greater balance between sugar content and fruit acidity.

Regarding antioxidant capacity, evaluated using the ferric reducing antioxidant power (FRAP) assay, a progressive increase was observed in response to increasing NPK fertilization rates. The highest values were recorded in treatments T4 and T5, with 25.64% and 26.23%, respectively, whereas T1 showed the lowest value (21.85%). These results indicate that increasing NPK fertilization rates differentially modified the physicochemical and antioxidant attributes of tomato fruits.

3.3. Effect of NPK on Mineral Composition

The composition and variation in mineral composition in tomato fruits showed marked differences among treatments (Table 4). Regarding macronutrients, the highest concentrations of calcium (Ca), potassium (K), and magnesium (Mg) were recorded in treatment T3 (186 kg N ha^{-1}, 165 kg P_2O_5 ha^{-1} y 270 kg K_2O ha^{-1}), with values of 3167.3, 78,487, and 3378.8 mg Kg^{-1}, respectively. These concentrations represented increases of 122.8 (Ca), 79.6 (K), and 116.8% (Mg) relative to T1 (86.8 kg N ha^{-1}, 77 kg P_2O_5 ha^{-1} y 126 kg K_2O ha^{-1}). In contrast, phosphorus (P) and sulfur (S) showed lower concentrations and negative variations compared to T1 in most treatments, with the exception of T4, which exhibited a slight positive variation of 7.5%.

For micronutrients, copper (Cu) concentration increased progressively up to T3, reaching 17.76 mg Kg^{-1}, which corresponded to a 42.3% increase compared to T1; however, at higher doses, Cu concentration declined. In contrast, iron (Fe) showed its highest concentration and variation in T2, with 17.76 ppm and an increase of 42.3%, respectively. Meanwhile, manganese (Mn) and zinc (Zn) concentrations were consistently lower than those observed in T1 across all treatments.

Table 4. Analysis of the concentrations and variations in mineral elements in tomato fruit.

Tra	Macronutrients (mg Kg^{-1})				
	Ca	**K**	**Mg**	**P**	**S**
T1	1421.4 (*)	43,700.5 (*)	1558.8 (*)	3855.1 (*)	10,068.1 (*)
T2	1588.2 (11.7)	35,131.3 (−19.6)	1502.5 (−3.6)	2976.9 (−22.8)	8136.9 (−19.2)
T3	3167.3 (122.8)	78,487.8 (79.6)	3378.8 (116.8)	3604.8 (−6.5)	9430.5 (−6.3)
T4	1271.2 (−10.6)	34,156 (−21.8)	1370.9 (−12.1)	2925.3 (−24.1)	10,825.1 (7.5)
T5	1494.7 (5.2)	35,499.6 (−18.8)	1568.1 (0.6)	3437.9 (−10.8)	8593.4 (−14.6)
Tra	**Micronutrients (mg Kg^{-1})**				
	Cu	**Fe**	**Mn**	**Zn**	
T1	12.48 (*)	329.4 (*)	79.1 (*)	44.1 (*)	
T2	14.26 (14.3)	482.3 (46.4)	34.9 (−55.9)	39.8 (−9.7)	
T3	17.76 (42.3)	283.4 (−14)	66.6 (−15.8)	39.5 (−10.6)	
T4	11.4 (−8.7)	280.3 (−14.9)	30.2 (−61.9)	33.9 (−23.2)	
T5	11.74 (−6)	303.5 (−7.9)	46.8 (−40.9)	36.9 (−16.3)	

Tra: Treatment. *: variation (%). Values represented in blue indicate positive variability compared with treatment 1, whereas values shown in red represent negative variability relative to that treatment.

3.4. Multivariate Analysis

Multivariate analyses using principal component analysis (PCA), based on morpho-physiological responses, yield, fruit quality, and mineral composition, revealed distinct patterns of association between the treatments and the evaluated variables (Figure 9A–C). In the PCA corresponding to morphophysiological and yield variables, treatment T3 showed a strong association with the main morphological and productive variables. In particular, T3 was closely associated with plant height (PH), number of inflorescences (NInf), number of flowers (NFl), and leaf area (LA). In contrast, treatments T4 and T5, corresponding to the highest NPK application rates, showed a greater association with physiological variables, indicating a differentiated plant response under elevated nutrient levels. The first two principal components explained 94.7% of the total variance, with PC1 and PC2 accounting for 57.6% and 37.1%, respectively (Figure 9A).

Regarding the PCA based on fruit quality attributes, the variables were widely dispersed, with only weak associations with some treatments (Figure 9B). The sugar-acid ratio (SAR) showed a particularly strong association with treatment T3, whereas antioxidant capacity determined by FRAP was more closely associated with T5. This pattern suggests that different NPK application rates may differentially modulate fruit quality attributes. PC1 and PC2 explained 90.5% and 8.0% of the total variance, respectively, accounting for 98.5% of the observed variation (Figure 9B).

On the other hand, the PCA based on fruit mineral concentrations showed a strong association between treatment T3 and most of the macro- and micronutrients evaluated (Figure 9C). In particular, the macronutrients Ca, Mg, and K, as well as the micronutrients Cu and Zn, were closely associated with T3, indicating that this fertilization rate favored greater accumulation of mineral elements in the fruits. PC1 and PC2 explained 52.2% and 22.0% of the total variance, respectively, accounting for 74.2% of the total variation (Figure 9C).

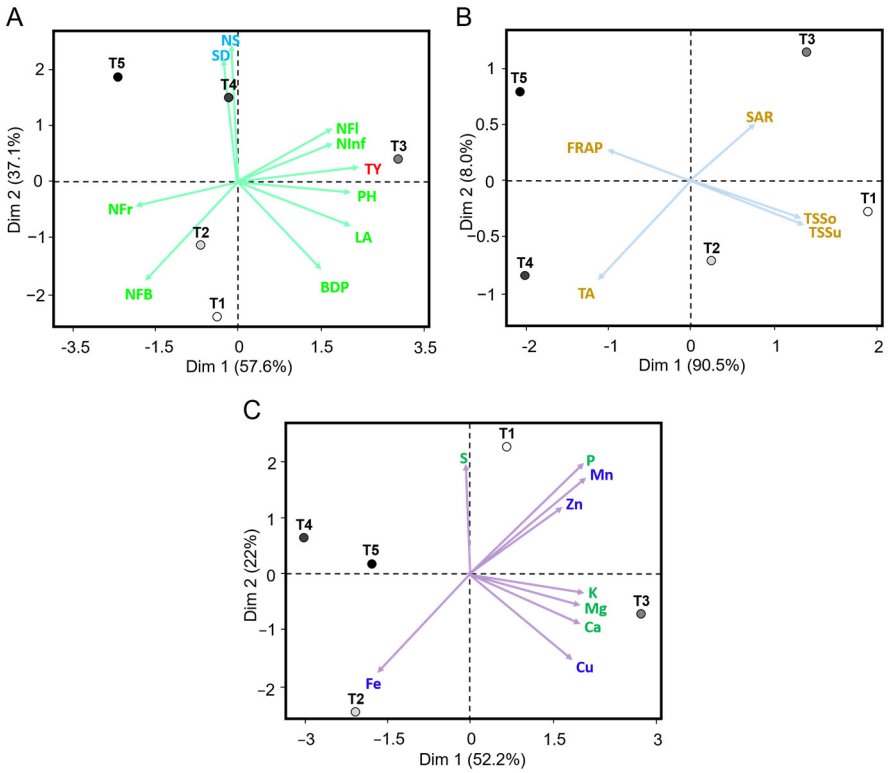


Figure 9. Principal component analysis of morphophysiological responses (**A**), fruit quality (**B**), and mineral composition of tomato fruit (**C**).

Spearman correlation analysis (ρ) revealed a total of 73 positive and 58 negative correlations among the evaluated variables (Figure 10). Among the morphological traits, plant height (PH), leaf area (LA), and number of inflorescences (NInf) showed positive correlations with tomato yield (TY), with ρ values of 0.97, 0.67, and 0.62, respectively. In contrast, the number of flower buds (NFB) and number of fruits (NFr) showed negative correlations with yield, with ρ values of −0.62 and −0.67, respectively.

For the physiological traits, both stomatal number (NS) and stomatal density (SD) showed positive correlations with titratable acidity (TA), with ρ = 0.72 in both cases. Total soluble solids (TSSo) and total soluble sugars (TSSu) showed positive correlations (ρ = 1). Similarly, antioxidant capacity assessed by FRAP showed a positive correlation with TA (ρ = 0.72), but negative correlations with total soluble solids (TSSo), total soluble sugars (TSSu), and the sugar-acid ratio (SAR), with ρ values of −0.90, −0.90, and −0.80, respectively.

Among the fruit quality attributes, SAR showed strong positive correlations with TSSo and TSSu (ρ = 0.90 in both cases) and with LA (ρ = 0.80). These associations indicate a close relationship between vegetative development and the balance among fruit components related to flavor.

Regarding the macronutrients, potassium (K) and phosphorus (P) showed positive correlations with basal stem diameter (BDP) (ρ = 0.60 and 0.70, respectively) and LA (ρ = 0.70 and 0.60, respectively). Both macronutrients also showed positive correlations with TSSo (ρ = 0.60 and 0.70), TSSu (ρ = 0.60 and 0.70), and SAR (ρ = 0.80 and 0.90), respectively. In addition, K and P exhibited a strong positive correlation with each other (ρ = 0.90).

Among the micronutrients, copper (Cu), manganese (Mn), and zinc (Zn) showed positive correlations with LA (ρ = 0.80, 0.60, and 0.60, respectively), TSSo (ρ = 0.60, 0.70, and 0.80), TSSu (ρ = 0.60, 0.70, and 0.80), and SAR (ρ = 0.70, 0.90, and 0.90). Furthermore,

Cu and Mn showed positive correlations with K (ρ = 0.70 and 0.90, respectively). In contrast, Zn showed a strong negative correlation with FRAP (ρ = −0.90).

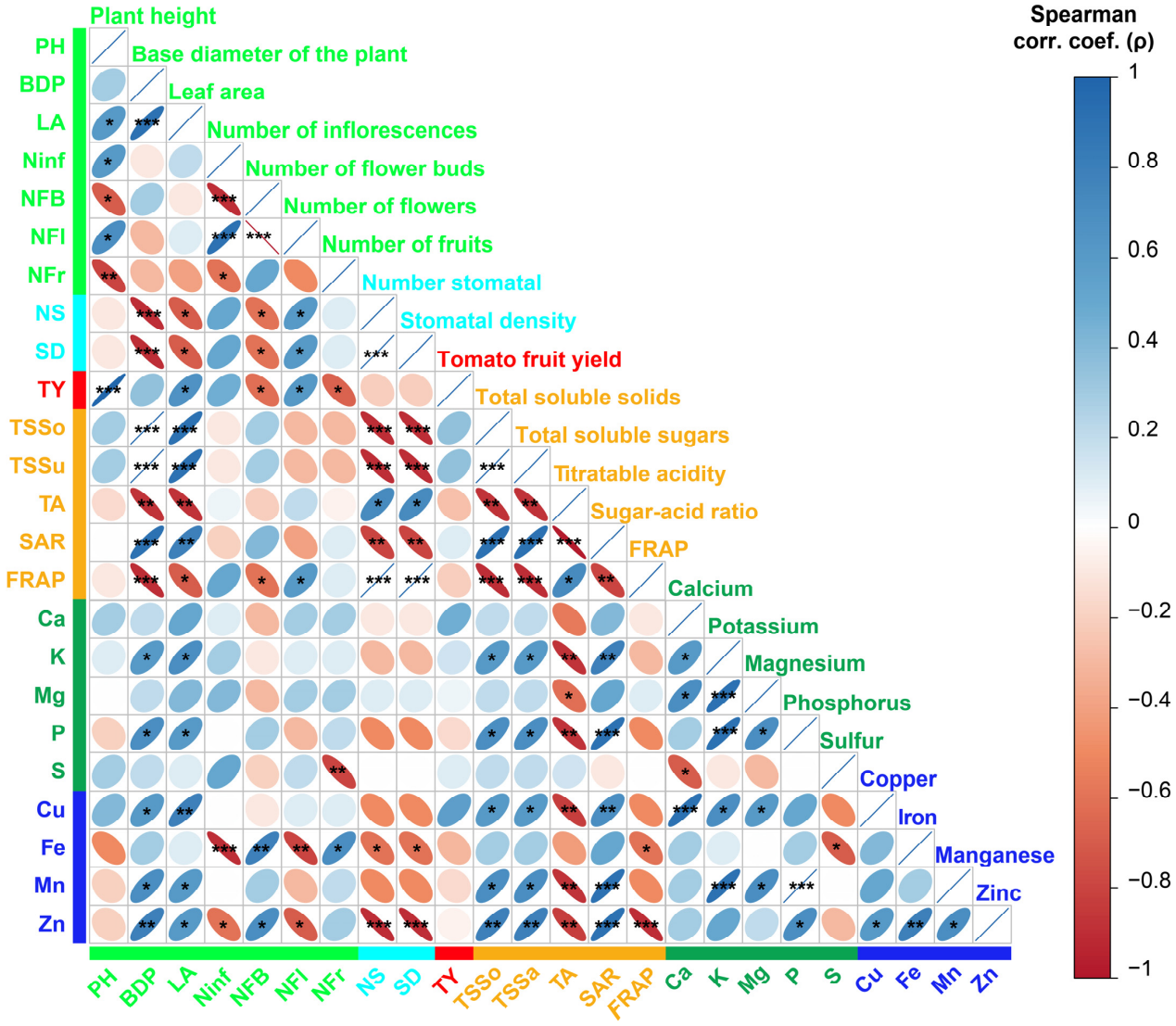


Figure 10. Correlation analysis. Asterisks (*, **, and ***) indicate low (0.60–0.74), moderate (0.75–0.89), and high correlations (greater than 0.90), respectively.

4. Discussion

4.1. Effect of NPK on Morphophysiological and Yield Parameters

Morphological, physiological, and yield-related traits in plants are strongly influenced by the availability and balance of nutrients supplied through fertilization [30]. In the present study, increasing NPK application rates resulted in a nonlinear response in tomato growth and productivity, with the best overall performance observed under T3 (1500 kg ha^{-1} of fertilizer; 186–165–270 kg ha^{-1} of N–P_2O_5–K_2O). This fertilization rate particularly enhanced plant height, leaf area, number of inflorescences, and number of flowers, whereas higher application rates did not provide proportional additional benefits. Similar results were reported by Dalal et al. [31] in *Brassica juncea* (L.), in which moderate NPK rates promoted plant development. In tomato, Ameta et al. [32] also observed a favorable growth response to fertilization, although at a rate of 225–125–125 kg ha^{-1} of N–P–K. The differences between their findings and those of the present study may be related to the edaphoclimatic conditions

of the experiments, particularly water availability, soil characteristics, and evaporative demand, which can influence nutrient uptake and utilization.

With respect to physiological responses, a progressive increase in stomatal number and density was observed with increasing NPK rates, with the highest values recorded under T5 (2500 kg ha^{-1}). This pattern suggests that nutrient availability may modify stomatal traits, potentially influencing gas exchange capacity. Wang et al. [33] reported that greater stomatal density may be associated with enhanced photosynthetic capacity, whereas Chun-Rong et al. [34] observed similar responses in *Zea mays* L. under increased nitrogen availability. However, the progressive increase in stomatal traits observed under T5 was not accompanied by greater productivity. Maximum yield was achieved under T3, reaching 52,666.7 kg ha^{-1} (52.67 t ha^{-1}), whereas T5 showed a reduction of approximately 32.28% relative to T3. This response indicates that greater NPK availability does not necessarily translate into increased productivity and that, under the conditions evaluated, T3 provided a more favorable nutritional balance for coordinating vegetative and reproductive growth.

The reduction in yield under the highest fertilization rates may be associated with alterations in nutrient balance and soil physicochemical conditions, including potential salt accumulation and nutrient uptake imbalances [35]. These conditions may increase physiological stress and promote the generation of reactive oxygen species, potentially affecting essential cellular and metabolic processes [36]. However, this mechanism was not directly evaluated in the present study and should therefore be considered as a possible explanation rather than a demonstrated causal mechanism. Further studies integrating physiological and biochemical measurements are recommended to better understand tomato responses to different NPK rates. Assessing gas exchange, chlorophyll content, and photosystem II photochemical efficiency would help determine the effects of fertilization on photosynthetic performance. In addition, analyzing nutrient concentrations in plant tissues, soil pH and electrical conductivity, as well as oxidative stress indicators and antioxidant activity, would help identify potential nutritional imbalances or salt accumulation associated with reduced yields under higher NPK rates. Integrating these variables would help clarify the relationships between mineral nutrition, physiological functioning, and tomato productivity, supporting the development of more precise fertilization recommendations.

Furthermore, the correlation analyses and three-dimensional response surface models supported the relationship between vegetative development and productivity. The model showed a strong fit ($R^2 = 0.86$; $p < 0.001$), indicating that higher tomato yields were associated with a favorable combination of plant height and leaf area.

4.2. Effect of NPK Fertilization on Tomato Fruit Quality Based on Physicochemical Attributes and Antioxidant Activity

Fruit quality is a key factor determining the commercial value and marketability of tomatoes, particularly for fresh consumption and export. Several studies have demonstrated that fertilization rates can modify fruit physicochemical attributes, particularly total soluble solids (TSSo) and total soluble sugars (TSSu) [37]. In the present study, increasing NPK fertilization rates resulted in a slight decrease in TSSo and TSSu values. Similar results were reported by Brunetto et al. [38] and Nava et al. [39] in *Citrus sinensis* and *Malus domestica*, respectively. Nevertheless, Mao et al. [40] reported that controlled and balanced fertilizer application can promote the accumulation of TSS and soluble sugars in fruits. In the present study, treatments T1 (700 kg ha^{-1}) and T3 (1500 kg ha^{-1}) exhibited the highest TSSo values (6.2 and 6.1 °Brix, respectively) and TSSu values (4.39 and 4.32%, respectively). These treatments also showed the lowest titratable acidity (TA), indicating a differential response of fruit quality attributes to NPK fertilization rates. The higher sugar concentrations and lower acidity observed under T1 and T3 may be associated with a more balanced mineral

nutritional status, which could favor the activity of enzymes involved in carbohydrate metabolism, such as sucrose synthase, sucrose-phosphate synthase, acid invertase, and neutral invertase. Likewise, adequate fertilization may influence the accumulation of organic acids, including tartaric, citric, acetic, malic, and shikimic acids, thereby affecting fruit flavor and organoleptic quality [13]. Regarding the sugar-acid ratio (SAR), a decreasing trend was observed as the NPK rate increased, although T3 showed an intermediate response relative to the fertilization rates evaluated. This finding suggests that higher fertilizer rates do not necessarily result in proportional improvements in fruit quality, as increased nutrient availability may elicit differential responses among the components determining the balance between sugars and acidity. In this context, T3 may represent a favorable nutritional condition by maintaining intermediate SAR values while also providing adequate performance across other fruit quality attributes.

Regarding antioxidant capacity determined by the ferric reducing antioxidant power (FRAP) assay, a progressive increase was observed with increasing NPK fertilization rates. This pattern may be associated with a greater capacity of plants to synthesize and accumulate phytochemicals with antioxidant activity, particularly polyphenols and flavonoids [41,42]. Likewise, high nutrient availability may induce a moderate level of metabolic stress that stimulates antioxidant defense mechanisms in plants. In this regard, increased fertilization may promote the production of reactive oxygen species (ROS), which could subsequently activate antioxidant responses involved in maintaining cellular homeostasis [43]. Therefore, the increase in FRAP observed under the higher NPK rates may reflect an adaptive response associated with the activation of secondary metabolism. However, this mechanism was not directly evaluated in the present study and should therefore be considered a possible explanation rather than a demonstrated causal mechanism.

Overall, the results demonstrated a modulatory effect of NPK fertilization on fruit quality attributes, with responses that did not follow a linear pattern across all variables evaluated. In particular, T3 (1500 kg ha^{-1}) showed a balanced response, combining adequate levels of soluble solids and sugars with low titratable acidity and favorable performance in other quality-related variables. This response suggests that an intermediate NPK fertilization rate may provide agronomic and quality advantages over excessively high rates by promoting a more favorable balance among productivity, physicochemical quality, and antioxidant capacity. Furthermore, correlation analyses and three-dimensional response surface models revealed positive associations between FRAP, TSSo, and TSSu and leaf area, with some of these relationships being statistically significant. These findings suggest that plant vegetative development, particularly leaf area expansion, may be associated with the accumulation of compounds related to fruit quality and antioxidant capacity. Greater leaf area may enhance radiation interception and photosynthetic capacity, potentially increasing the availability of photoassimilates for reproductive organs and, consequently, contributing to the accumulation of sugars and secondary metabolites in fruits. On the other hand, future studies should incorporate more detailed biochemical analyses to gain deeper insights into the effects of NPK fertilization on tomato fruit quality. In particular, individual quantification of soluble sugars (glucose, fructose, and sucrose), organic acids (citric and malic acids), phenolic compounds, and flavonoids is recommended, together with the determination of ascorbic acid, carotenoids (particularly lycopene and β-carotene), and other metabolites with bioactive potential. Additionally, the assessment of antioxidant capacity using complementary methods, such as DPPH and ABTS assays, would provide a more comprehensive characterization of the antioxidant properties of the fruits. Physical and commercial quality parameters, including firmness, instrumental color, pericarp thickness, individual fruit weight, and weight loss during storage, should also be evaluated. Although the present study represents an initial approach to assessing the effects of different NPK application

rates on tomato fruit quality, the progressive incorporation of these variables would expand our understanding of crop responses to fertilization and provide a foundation for future research aimed at comprehensively elucidating the relationships between mineral nutrition, fruit quality, and the functional potential of tomatoes.

4.3. Effect of NPK on Mineral Composition

The impact of fertilization on the mineral composition of fruits is an important aspect for understanding the nutritional response of the crop and its potential contribution to tomato quality. In the present study, the concentrations of the mineral elements evaluated differed among treatments, indicating a differential response to NPK fertilization rates. Among the macronutrients, treatment T3 (1500 kg ha^{-1}) showed the highest concentrations of calcium (Ca), potassium (K), and magnesium (Mg), reaching 3167.2, 78,487.8, and 3378.8 mg kg^{-1}, respectively. However, increasing the fertilization rate beyond T3 was accompanied by a decrease in the concentrations of these elements, with reductions of up to 10.6%, 21.8%, and 12.1% for Ca, K, and Mg, respectively, compared with T1. This pattern suggests that the application of high NPK rates does not necessarily promote greater mineral nutrient accumulation in fruits and that, beyond an optimal level, changes in the uptake, transport, and distribution of mineral elements may occur.

Previously reported Ca, K, and Mg concentrations in tomato fruits show considerable variability, ranging from 2000–3600, 1331.1–3025.2, and 4000–8000 mg kg^{-1}, respectively [44–46]. Compared with these values, the Ca concentration observed under T3 fell within the previously reported range, whereas the K concentration was considerably higher and the Mg concentration was lower. Compared with these previous reports, the Ca concentration observed under T3 falls within the previously reported range, whereas the K and Mg concentrations were considerably higher. From a nutritional perspective, Ca, K, and Mg are essential minerals for human health. Calcium is involved in fundamental processes such as cell signaling, muscle contraction, and cell division; potassium is the major intracellular cation and plays important roles in osmotic and electrical balance; while magnesium acts as a cofactor in numerous metabolic reactions related to energy production and other physiological processes [47–49]. In this context, the greater accumulation of these macronutrients observed under T3 is relevant from a nutritional quality perspective. However, the actual contribution of tomato fruits to daily nutrient requirements depends on their mineral concentration on a fresh-weight basis, the amount consumed per serving, and the bioavailability of each element. Therefore, the results suggest that T3 promoted macronutrient accumulation in the fruits, although its nutritional relevance should be interpreted in relation to actual tomato intake.

Regarding micronutrients, the response to fertilization was also differential. Treatment T3 showed the highest copper (Cu) concentration, reaching 17.76 mg kg^{-1}, which represented an increase of 42.3% relative to treatment T1. In contrast, treatment T2 (1000 kg ha^{-1}) showed the highest iron (Fe) concentration, reaching 482.3 mg kg^{-1}, whereas manganese (Mn) and zinc (Zn) exhibited different patterns, with higher concentrations associated with treatment T1 (700 kg ha^{-1}). In particular, Mn and Zn concentrations ranged from 30.2 to 66.6 and from 33.9 to 39.8 mg kg^{-1}, respectively. These differential responses suggest that NPK availability may influence micronutrient uptake and accumulation through interactions among mineral elements, competition for uptake sites, and regulatory mechanisms governing nutrient transport within the plant. Compared with the values reported by Tietel et al. [50], Erika et al. [44], and Shai et al. [51], the concentrations of Cu, Fe, Mn, and Zn observed in the present study were higher to varying degrees. This variability may be related to differences in plant material, edaphoclimatic conditions, fertilization management, fruit maturity stage, and, particularly, the basis used to express mineral concentrations.

The recommended daily intakes of Cu, Fe, Mn, and Zn for adults are approximately 0.9–1.3, 8–18, 2.3–3.0, and 8–11 mg day^{-1}, respectively, depending on factors such as age and sex [52–54]. Accordingly, fruits obtained under the different fertilization treatments could contribute to the dietary intake of these micronutrients; however, the magnitude of this contribution should be estimated based on mineral concentrations in fresh fruit and a typical serving size. In this regard, although T1 showed higher concentrations of some micronutrients, T3 exhibited a more balanced response by combining high accumulation of certain minerals with superior performance in the productive and quality-related variables evaluated. Therefore, T3 may represent a promising alternative for simultaneously optimizing yield and fruit mineral composition, although these findings should be complemented by assessments of mineral bioavailability and nutritional contribution per serving.

Furthermore, correlation analyses revealed associations between certain macronutrients, particularly K and Mg, as well as some micronutrients, and morphological and fruit quality variables, including plant height (PH), total soluble solids (TSSo), total soluble sugars (TSSu), and the sugar-acid ratio (SAR). These associations suggest that mineral nutrition and vegetative development may be closely related to the physicochemical composition of tomato fruits. In particular, the association between mineral concentrations and variables such as TSSo and TSSu may reflect interactions among the nutritional status of the plant, development of the photosynthetic area, and the availability of photoassimilates for fruit development. However, because correlation analyses do not establish causal relationships, these findings should be interpreted as evidence of associations between mineral nutrition and morphophysiological and fruit quality attributes.

Overall, the results demonstrate that NPK fertilization differentially modulates the accumulation of macro- and micronutrients in tomato fruits. The response observed under T3 was particularly notable because it provided a favorable balance among mineral composition, fruit quality attributes, and yield performance. These findings reinforce the importance of determining fertilization rates that maximize crop nutritional efficiency without inducing adverse responses associated with excessive nutrient application. Furthermore, future studies should incorporate assessments of mineral bioavailability and jointly evaluate biochemical variables, including individual sugars, carbohydrates, organic acids, phenolic compounds, and flavonoids, to provide a deeper understanding of the mechanisms through which NPK nutrition regulates the nutritional and functional quality of tomato fruits.

5. Conclusions

This study demonstrated that NPK fertilization modulates the morphophysiological parameters and fruit quality of tomato. In particular, the 1500 kg ha^{-1} rate promoted the best performance in morphological and yield parameters while maintaining relatively high and stable physiological levels. Regarding fruit quality, this fertilization rate showed a favorable response in physicochemical attributes and antioxidant capacity, while, in terms of mineral composition, it promoted greater accumulation of several mineral elements. Overall, these results indicate that the 1500 kg ha^{-1} rate provided a favorable balance among plant growth, productivity, physicochemical quality, antioxidant capacity, and fruit mineral composition. In contrast, NPK rates below or above 1500 kg ha^{-1} did not surpass the overall performance achieved at this rate. Therefore, the results demonstrate that appropriate NPK fertilization management represents an efficient agronomic strategy for optimizing crop productivity and enhancing the nutritional quality of tomato fruits.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/ijpb17110115/s1, Figure S1: Relationship of soluble solids and titratable acidity (A). Three-dimensional models of the interaction among plant height, leaf area and sugar-acid ratio (SAR) (B–F).

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