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Foliar nutrient-induced modulation of yield, juice quality and biochemical traits in Sweet Orange (*Citrus sinensis* Osbeck) cv. Malta

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Abstract

Foliar nutrient application plays an important role in citrus production, as nutrient availability influences fruit development, yield, juice quality, and biochemical composition. The present study evaluated the effect of foliar application of macro- and micronutrients on fruit yield and quality of sweet orange cv. Malta under West Bengal conditions. Thirteen nutrient treatments comprising K_2SO_4, KNO_3, $Ca(NO_3)_2$, $ZnSO_4$, H_3BO_3 and NPK (19:19:19) at different concentrations were evaluated. Significant variation was observed in fruit physical, biochemical, yield, and antioxidant attributes. K_2SO_4 @ 1.0 % recorded the highest fruit yield (17.04 kg/tree) and showed superior overall performance, while $ZnSO_4$ @ 2.0 % produced the highest fruit weight, diameter, juice content, and reducing sugar. H_3BO_3 @ 1.0 % recorded the highest total soluble solids (TSS) and ascorbic acid. Principal component analysis, correlation, and hierarchical clustering supported the observed treatment differences and identified strong associations among fruit size, yield, and quality traits.

Keywords: Malta, Foliar spray, nutrients, antioxident, multivariate analysis

Introduction

The genus Citrus, comprising approximately 159 species, represents one of the most economically important fruit groups cultivated worldwide (Richa et al. 2023). In India, citriculture constitutes a major component of the horticultural sector and ranks third in importance after mango and banana. Citrus cultivation covers more than 1.12 million hectares, with an annual production of approximately 14.87 million tonnes. Among the citrus fruits, sweet orange, is the second most important citrus fruit in the country after mandarins, with an annual production of approximately 3.87 million tonnes (MoA&FW 2025). Sweet orange is predominantly cultivated in Andhra Pradesh, Maharashtra, Punjab, and Rajasthan, while commercial cultivation on a smaller scale is also practiced in Uttarakhand, Arunachal Pradesh, and the northern parts of West Bengal. Sweet orange is an important fruit crops due to its high vitamin C content and consequently contributes significantly to nutritional health (Gregory 1993). In addition to vitamin C, the fruit contains a diverse array of bioactive and nutritional constituents, including phenolic compounds, proteins, minerals, vitamins, pigments, volatile compounds, lipids, carbohydrates, organic acids, and dietary fibre (Bampidis and Robinson 2006). These organic and inorganic constituents are associated with a broad range of pharmacological benefits, including antioxidant and anti-inflammatory activities, protection against cardiovascular disorders, prevention of neurodegenerative diseases, and potential anti-carcinogenic effects (Saini et al. 2022).

Due to its high demand, consumer acceptability, and commercial viability, sweet orange cultivation is expanding into non-traditional growing areas. In West Bengal, however, official production data for sweet orange alone are not available. In recent years, farmers have increasingly adopted citrus cultivation alongside mango as a supplementary income-generating activity, contributing to farm income diversification and enhancing economic resilience. Despite the increasing adoption of sweet orange cultivation in the areas, farmers have reported poor fruit quality, Poor fruit quality may be associated with soil-related constraints, particularly in calcareous and alkaline soils, where nutrient availability and uptake can be restricted (Zekri and Obreza 2003). Essential macro and micronutrients are required for various physiological and metabolic processes, including photosynthesis, enzyme activity, carbohydrate metabolism, cell division, and fruit development. Therefore,

maintaining an adequate and balanced supply of nutrients is important for achieving optimum fruit yield and quality. Foliar application provides a practical approach for supplying nutrients directly to plant tissues, enabling rapid nutrient absorption and response and potentially improving nutrient use efficiency, particularly when soil conditions limit nutrient availability (Fernandez et al. 2013; Obreza et al. 2010). Several studies have reported that foliar application of nutrients can improve fruit size, TSS, juice quality, and other quality attributes in citrus (Abd-El-Rahman et al. 2012; Zai et al. 2021; Farooq et al. 2023). However, comparative information on the response of sweet orange (Malta) to foliar application of different macro and micronutrients under non-traditional growing conditions, particularly in West Bengal, remains limited.

Therefore, the present study was undertaken to evaluate the effect of foliar application of macro and micronutrients on fruit morpho-pomological, biochemical parameters and yield of sweet orange grown under West Bengal conditions.

Materials and Methods:

Plant materials:

The experiment was conducted during 2022 in a farmer's field at Madanpur, North 24 Parganas, West Bengal, India. The experimental site was located at 22°92′46″ N latitude and 88°53′80″ E longitude, at an elevation of 9.67 m above mean sea level. The experiment was carried out in the year 2022 during the Ambe bahar season using three-year-old plants of sweet orange (*Citrus sinensis* Osbeck) cv. Malta grafted on Pummelo seedling. The region has a humid subtropical climate, characterized by Summer (February to May), Rainy (June to October) and Winter (November to January). The weather conditions and soil properties of the experimental site during the evaluation period are given in the Supplementary Fig. 1 and Supplementary Table 1. The experimental site is located in the Gangetic new alluvial plains (Entisol) of West Bengal. The topographic situation of the site is characterized by clay loam soil texture.

For precise assessment of physical and biochemical quality attributes and to minimize the influence of tree position effects, fruits were harvested from all sides of the tree canopy during the 3rd and 4th week of October at the optimum mature stage. The sampling was carried out randomly and the harvested fruits were taken to the departmental laboratory, washed with distilled water, dried with tissue paper, and analyzed for various parameters.

Crop management and treatment

All the grafted trees were maintained under standardized irrigation and fertilizer management practices, in accordance with the technical recommendations for citrus in the same agro-climatic region. Farmyard manure (FYM) was applied uniformly to all experimental plants at 10 kg plant per plant during the second week of February (Supplementary Fig 2, followed by irrigation. Two foliar applications of the respective nutrient treatments were made. The details of the concentration of the all the treatment is given in the Table 1. The first application was carried out at the flowering stage during the third week of February, followed by a second application 15 days later. Control plants received FYM but no foliar nutrient application. Irrigation was provided at approximately 7-8 day intervals during summer and 15-day intervals during the rainy season.

Table 1 Treatment details of different macro and micro nutrients use for the experiment.

Notation	**Treatment details**
T_1	Control (Only FYM)
T_2	Potassium sulphate (K_2SO_4) @ 0.5 %
T_3	Potassium sulphate (K_2SO_4) @ 1.0 %
T_4	Potassium nitrate (KNO_3) @ 1.0 %
T_5	Potassium nitrate (KNO_3) @ 2.0 %
T_6	Calcium nitrate ($Ca(NO3)_2$) @ 0.5 %
T_7	Calcium nitrate ($Ca(NO3)_2$) @ 1.0 %
T_8	Zinc sulphate ($ZnSO_4$) @ 1.0 %
T_9	Zinc sulphate ($ZnSO_4$) @ 2.0 %
T_{10}	Boric acid (H_3BO_3) @ 0.5 %
T_{11}	Boric acid (H_3BO_3) @ 1.0 %
T_{12}	NPK (19:19:19) @ 0.5 %
T_{13}	NPK (19:19:19) @ 1.0 %.

Observations recorded

Morpho-pomological parameters

Fruit and peel weights were recorded using a digital weighing balance. Fruit length and diameter were measured with a calibrated digital vernier caliper (Mityuto, Japan). Fruit volume was estimated by the water displacement method. For this, clean, freshly harvested fruits were completely immersed in an Eureka can filled with water, and the displaced water was collected in a graduated measuring cylinder. The volume of water displaced was considered equivalent to the volume of the fruit. Juice was extracted from the fruits using a citrus juicer. The extracted juice was weighed, and juice content was expressed as a percentage of the total fruit weight using the following formula:

$$\text{Juice \%} = \frac{\text{Juice weight}}{\text{Total weight of fruit}} \times 100$$

Fruit yield and retention

Fruits were harvested at the appropriate maturity stage based on the acid/TSS ratio, with harvesting carried out at two different harvests. The total fruit yield per tree was recorded. For determining fruit retention, healthy fruit-bearing shoots were randomly selected and tagged in each of the four cardinal directions (North, South, East, and West). The number of fruits borne on each tagged shoot was recorded at fruit set and subsequently counted again at harvest. Fruit retention percentage was calculated using the following formula:

$$\text{Fruit retention \%} = \frac{\text{Number of fruits at harvest}}{\text{Number of fruits at fruit set}} \times 100$$

Biochemical parameters

Total soluble solids (TSS) were measured using a digital refractometer and expressed in °Brix. Prior to measurement, the refractometer was calibrated using distilled water followed by a standard sugar solution of known concentration. Titratable acidity (TA) was estimated and expressed as percentage citric acid following the AOAC method (AOAC 2000a). Briefly, 5 mL of clarified fruit juice was titrated against 0.1 N sodium hydroxide (NaOH), using phenolphthalein as the indicator. The titratable acidity was calculated using the following formula:

$$\text{\% citric acid} = \frac{\text{Titrate} \times \text{Normality of alkali} \times \text{Volume made up} \times \text{Eq .wt .of acid} \times 100}{\text{V (aliquot taken)} \times \text{W (sample)} \times 1000}$$

where V (aliquot) = 10 mL and W (sample) = 5 mL juice.

The maturity index (MI) was considered as the ratio of total soluble solids (°Brix) to titratable acidity expressed as percentage citric acid. Ascorbic acid content was estimated according to AOAC method (AOAC 2000b). Fresh fruit juice (10 mL) was mixed with an equal volume (10 mL) of 3 % (w/v) metaphosphoric acid to minimize oxidation of ascorbic acid. After clarification, a 10 mL aliquot of the extract was titrated against standardized 2,6-dichlorophenol indophenol (DCPIP) dye solution. Titration was continued until a light pink colour persisted for approximately 10-15 seconds. The DCPIP solution was standardized against AR-grade ascorbic acid. The ascorbic acid content was expressed as mg/100 mL of juice. The dye factor was calculated as 0.5 divided by the titre value and was determined as 0.07 based on standardization of the DCPIP solution against a known concentration of ascorbic acid standard.

Sugar content was determined using the titration procedure described by Lane and Eynon (1923). This method relies on the reduction of Cu^{2+} ions in Fehling's solution to insoluble, reddish-colored cuprous oxide (Cu_2O) when reducing sugars are present. Prior to titration, the juice samples were treated to convert non-reducing sugars into reducing forms through acid hydrolysis. This involved treating an aliquot of clarified juice with concentrated HCl, then neutralizing it with 0.1N NaOH. The resulting solution was then titrated against freshly boiled Fehling's solution, with methylene blue serving as the indicator.

$$\text{Total sugar \%} = \frac{(\text{Fehling's factor} \times \text{Dilution factor})}{\text{Titre value} \times \text{Volume of extract}} \text{ x } 100$$

To estimate reducing sugars, 25 mL of fruit juice was placed in a 250 mL volumetric flask, followed by the addition of 2 mL each of lead (II) acetate (45% w/v) and potassium oxalate (22 % w/v) solutions. The flask was then topped up to volume with distilled water. This mixture was left to stand for 15-20 minutes to allow precipitation to occur, after which it was filtered. Separately, 2.5 mL each of Fehling's solution A and solution B were combined with 50 mL distilled water in another flask. This solution was brought to the point of boiling, 1-2 drops of methylene blue indicator were introduced, and the filtrate from the first flask was used to titrate the mixture until a brick-red color developed, indicating the endpoint.

$$\text{Reducing sugars } \% = \frac{(\text{Fehling's factor} \times \text{Dilution factor}) \text{ x } 100}{(Titre\ value \times Volume\ of\ extract) \times 50} \ x\ 100$$

The concentration of non-reducing sugars (NRS; percent) was determined by the equation, where 0.95 is the sucrose correction factor (0.95 g sucrose on hydrolysis yields 1 g invert sugars):

$$\text{Nonreducing sugars \%} = (\text{Total sugars} - \text{reducing sugars}) \times 0.95$$

Ferric reducing activity was assessed using the FRAP assay described by Benzie and Strain (1996), with minor modifications. The FRAP reagent was freshly prepared by combining 300 mM acetate buffer (pH 3.6), 10 mM TPTZ (2,4,6-tripyridyl-s-triazine) in 40 mM HCl, and 20 mM $FeCl_3 \cdot 6H_2O$ at a ratio of 10:1:1 (v/v/v). Briefly, 0.1 mL of fruit extract was added to 3 mL of FRAP reagent, vortexed, and incubated in the dark for 30 min. The resulting blue-colored ferrous-TPTZ complex was measured at 593 nm using a UV–Vis spectrophotometer (SHIMADZU, Japan). Antioxidant capacity was quantified using a Trolox calibration curve and expressed as µmol Trolox equivalents per gram fresh weight (µmol TE/g FW).

Statistical analysis

The experiment was conducted in a Randomized Block Design (RBD) comprising 13 treatments and three replications. Ten fruits were randomly selected from each replication for recording the fruit quality and biochemical parameters. The data were subjected to analysis of variance (ANOVA) using RStudio (version 2022.07.1-554, RStudio PBC) to determine the significance of treatment effects. When significant differences were observed, treatment means were compared using the least significant difference (LSD) test at the 5 % level of significance. Principal component analysis (PCA) was performed to identify the major sources of variation and to examine the relationships among the studied traits and treatments. The distribution of treatments and contribution of individual traits were evaluated based on the principal components. Pearson's correlation coefficient (r) was calculated to determine the strength and direction of associations among the evaluated fruit and biochemical traits. The correlations were visualized using a correlation heatmap, and their significance was indicated at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

An agglomerative hierarchical clustering (AHC) analysis was also performed to classify the treatments according to the similarity of their measured characteristics. Euclidean distance was used as the dissimilarity measure, and Ward's D2 method was used as the linkage criterion. The clustering results were presented as a heatmap to visualize the grouping of treatments based on the evaluated traits.

Results and Discussion

Significant variation was observed among the nutrient treatments for the studied fruit physical parameters and biochemical parameters (Table 2; Fig. 1). Fruit weight ranged from 186.63 to 209.97 g, with the maximum fruit weight recorded under $ZnSO_4$ @ 2.0 % (T_9; 209.97 g), followed by $ZnSO_4$ @ 1.0 % (T_8; 206.94 g), whereas the control (T_1) recorded the lowest fruit weight (186.63 g). The differences among treatments were significant. Similarly, fruit diameter was maximum under $ZnSO_4$ @ 2.0 % (T_9; 7.58 cm), while the control recorded the minimum diameter (6.93 cm). The increase in fruit weight and diameter with zinc application may be attributed to the role of zinc as a cofactor in tryptophan synthesis, which contributes to auxin (IAA) biosynthesis and subsequently promotes cell division and elongation, resulting in enhanced fruit growth (Alferez et al. 2023). Supporting this mechanism, Razzaq et al. (2013) reported that foliar application of 0.6 % zinc sulphate resulted in the highest increase in fruit diameter and fruit weight in Kinnow mandarin. Similarly, Mehta et al. (2025) reported an improvement in physical fruit characteristics of guava with zinc application, further supporting the positive influence of zinc on fruit growth and development.

Fruit length was highest under K_2SO_4 @ 1 % (T_3; 7.61 cm), which was statistically at par with T_2 (K_2SO_4 @ 0.5 %), T_8 (ZnSO4 @ 1.0 %) and T_{10} (B @ 0.5 %), while the control recorded the lowest length (6.73 cm). Fruit volume was maximum with K_2SO_4 @ 0.5 % (T_2; 167.05 cm^3), at par with $ZnSO_4$ @ 2.0 % (T_9; 166.33 cm^3), whereas the control recorded the lowest volume (146.00 cm^3). The improvement in fruit length with potassium may be attributed to enhanced enzyme activity, photosynthesis and translocation of photoassimilates to the fruit, promoting cell division and expansion (Havlin et al. 2016). Boron may further enhance fruit elongation through its role in auxin-mediated cell division and elongation (Stoller et al. 2005). Similar improvements in fruit length and volume with foliar potassium application have been reported in guava (Singh and Kaur 2026) and pear (Gill et al. 2012). The greater fruit volume under and $ZnSO_4$ treatments may result from enhanced assimilate translocation and zinc-mediated auxin synthesis, promoting cell expansion.

Peel weight showed considerable variation, ranging from 28.48 to 44.23 g. The maximum peel weight was recorded with K_2SO_4 @ 1.0 % (T_3; 44.23 g), followed

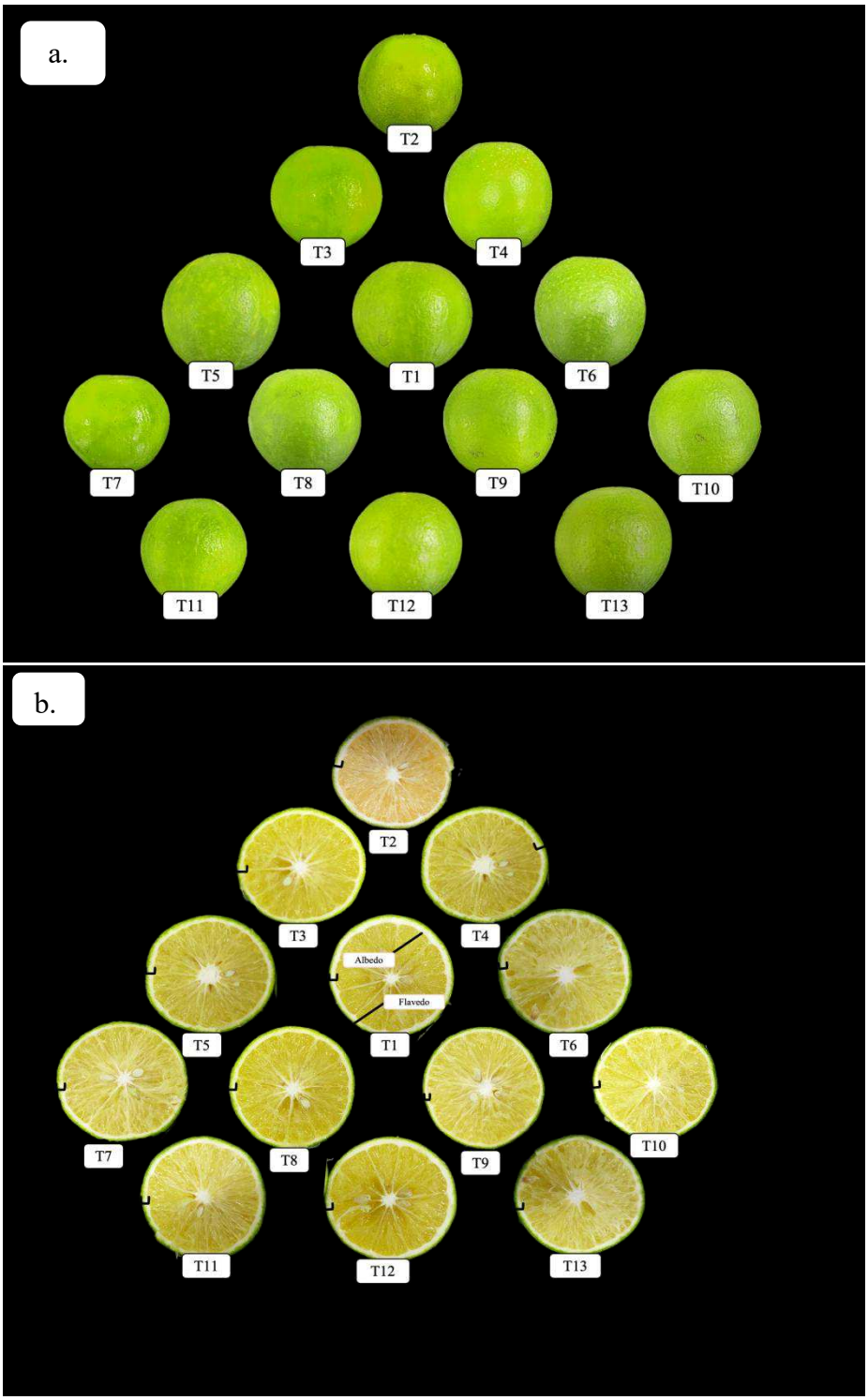


Fig. 1 Pictorial representation of fruits under different treatments (T_1-T_{13}). a: Whole fruit images showing external morphology and color variation across treatments, b: Representative cross-sectional images.

by the control (T_1; 40.49 g), whereas the minimum was observed with $ZnSO_4$ @ 2.0 % (T_9; 28.48 g), which was statistically at par with $ZnSO_4$ @ 1.0 % (T_8; 28.78 g) and $Ca(NO_3)_2$ @ 1.0 % (T_7; 29.21 g) (Fig. 2). The higher peel weight under potassium application may be attributed to its role in promoting cell division and increasing peel thickness and strength, consistent with reports of thicker peels under potassium application (Ashraf 2009) and increased peel:pulp ratio following K_2SO_4 application during fruit development (Thu et al. 2024). In contrast, the lower peel weight under $ZnSO_4$ treatments aligns with Liaquat et al. (2021), who reported reduced peel weight and peel:pulp ratio in Kinnow mandarin following $ZnSO_4$ application. Jiao et al. (2023) reported greater calcium accumulation in the peel. From a quality perspective, peel thickness is an important trait that varies with citrus type and market requirements; while thicker peels can improve resistance to pests, handling damage and extend shelf life, however, excessive peel thickness may be less desirable for fresh consumption.

Among the treatments, potassium sulphate K_2SO_4 @ 0.5 % (T_2) recorded the highest fruit retention at all observation stages (Fig. 2), followed by calcium nitrate [$Ca(NO_3)_2$] @ 1.0 % (T_7), both significantly superior to the control (T_1). Fruit yield varied substantially among treatments, ranging from 12.46 to 17.04 kg/tree) The highest fruit yield was obtained with K_2SO_4 @ 1.0 % (T_3; 17.04 kg tree), followed by $ZnSO_4$ @ 2.0 % (T_9; 16.51 kg/tree) and $ZnSO_4$ @ 1.0 % (T_8; 15.64 kg/tree). K_2SO_4 @ 0.5 % (T_2; 15.31 kg/tree) and KNO_3 @ 2.0 % (T_5; 15.13 kg/tree) also produced comparatively higher yields. The control recorded the lowest yield (12.46 kg/tree). Abd-El-Rahman et al. (2012) reported that foliar-applied potassium nitrate at 2 - 6 % significantly improved fruit set, fruit size, and yield in Washington navel orange (*Citrus sinensis*). A single 4 % KNO_3 spray at full bloom increased total yield by about 53 % compared with the control, mainly through higher fruit number per tree. Baloda et al. (2024) also found increased fruit weight, length, breadth and over all yield with $ZnSO_4$ application in guava.

Juice percentage ranged from 37.20 to 47.43 %, with the highest juice recovery recorded under $ZnSO_4$ @ 2.0 % (T_9; 47.43 %), followed by H_3BO_3 @ 0.5% (T_{10}; 46.40%) and $ZnSO_4$ @ 1.0% (T_8; 46.23 %). The control recorded substantially lower juice recovery (37.20 %). The higher juice recovery with $ZnSO_4$ application is supported by previous findings. Ashraf et al. (2013b) reported that foliar application

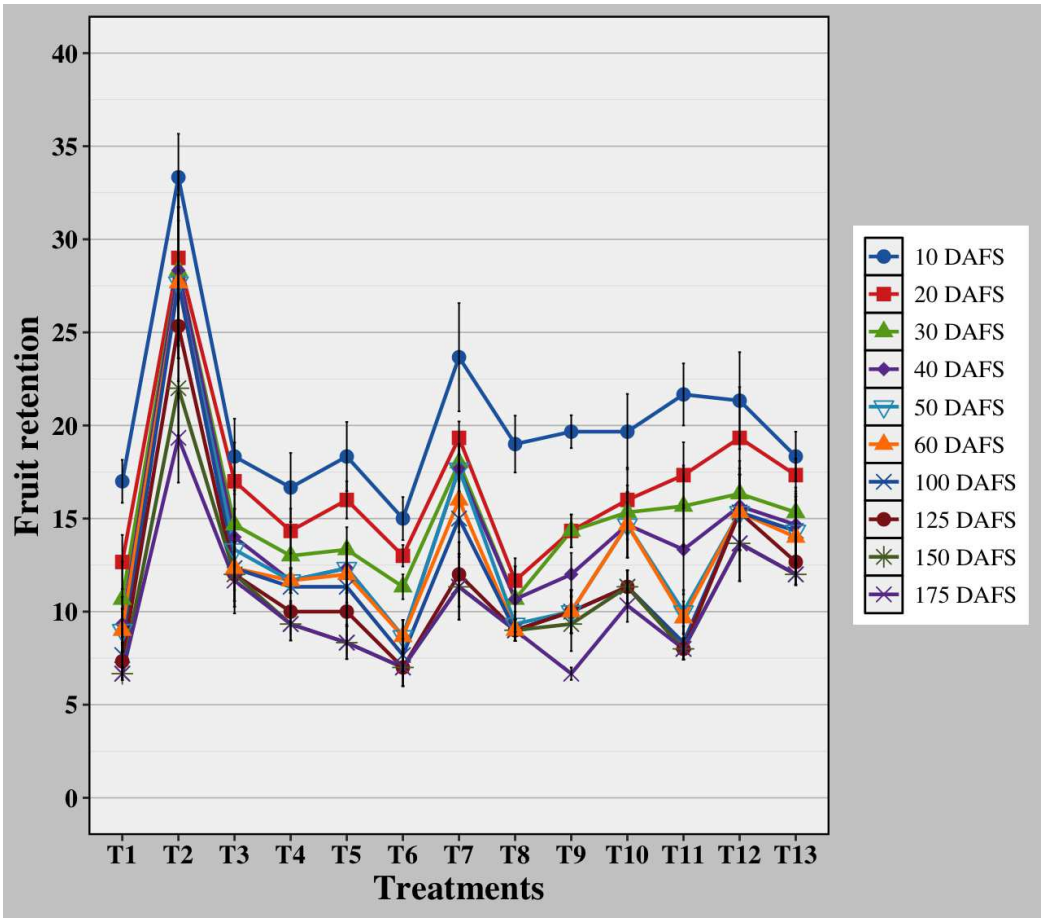


Fig. 2 Effect of different nutrient sprays on fruit retention (%) in Malta. (DAFS: Days after fruit set).

of 0.8 % $ZnSO_4$ increased juice weight percentage by 25.86 % compared with the control in 'Kinnow' mandarin. Similarly, Zn application was reported to increase juice weight percentage in 'Khasi' mandarin (Babu and Yadav 2005). Ashraf et al. (2013a) also recorded the highest juice volume in acid lime with foliar application of Zn + K. Furthermore, combined application of Mg, Cu, Zn, Fe and B increased juice content in fruit (Ram and Bose 2000). The higher juice recovery observed with $ZnSO_4$ and boron application in the present study may therefore be associated with improved fruit development and juice accumulation.

The highest ascorbic acid content was recorded with Boron @ 1.0 % (T_{11}; 49.78 mg/100 mL), followed by $ZnSO_4$ @ 2.0 % (T_9; 47.19 mg/100 mL), K_2SO_4 @ 1.0 % (T_3; 46.85 mg/100 mL), and NPK @ 1.0 % (T_{13}; 46.30 mg/100 mL), while the control recorded a comparatively lower value (41.50 mg/100 mL). The higher ascorbic acid content observed with H_3BO_3 and $ZnSO_4$ application is consistent with Khan et al. (2015), who reported a 1.3-fold increase in ascorbic acid content with their application, either alone or in combination, in 'Kinnow' mandarin. Similarly, Kumari et al. (2024) observed increased ascorbic acid content with B and Zn application in 'Kinnow' mandarin, while Tripathi and Nand (2022) reported the maximum ascorbic acid content with borax, followed by ZnSO, application in aonla. The role of boron may be attributed to its role in stabilizing ascorbic acid and delaying its degradation (Álvarez-Herrera et al. 2025). Furthermore, boron is involved in antioxidant-related enzymatic and metabolic pathways and interacts with nutrients such as Ca, N, P, K, and Zn, which may contribute to enhanced accumulation and maintenance of ascorbic acid (Vera-Maldonado et al. 2024). While, beneficial effect of Zn may be associated with its role in auxin biosynthesis, as increased auxin production has been linked with enhanced ascorbic acid accumulation in 'Kinnow' mandarin (Cakmak et al. 1989; Nawaz et al. 2008). In addition, Ashraf et al. (2013a) found increased concentration of ascorbic acid in acid lime with foliar application of Zn, K or Zn + K in combination .

The highest TSS was recorded with H_3BO_3 @ 1.0 % (T_{11}; 10.23 °Brix), closely followed by K_2SO_4 @ 1.0 % (T_3; 10.10 °Brix), with both treatments being statistically at par. In contrast, the control recorded the lowest TSS (8.01 °Brix). Acidity was highest in the control (0.31 %), whereas the lowest acidity (0.19 %) was recorded with KNO_3 @ 1.0 % (T_4), $ZnSO_4$ @ 2.0 % (T_9), and H_3BO_3 @ 0.5 % (T_{10}), indicating that several nutrient treatments reduced fruit acidity compared with the control. Total sugar was highest under K_2SO_4 @ 1.0 % (T_3; 5.05 %), followed by

H_3BO_3 @ 1.0 % (T_{11}; 4.91 %) and $ZnSO_4$ @ 2.0 % (T_9; 4.89 %), while reducing sugar was highest with $ZnSO_4$ @ 2.0 % (T_9; 3.62 %). K_2SO_4 @ 1.0 % (T3; 3.45 %), K_2SO_4 @ 0.5 % (T2; 3.36 %), and $Ca(NO_3)_2$ @ 1.0 % (T_7; 3.32 %) also recorded relatively high reducing sugar contents. Non-reducing sugars ranged from 0.95 to 1.87 %, with the highest value under H_3BO_4 @ 0.5 % (T_{10}; 1.87 %), followed by $ZnSO_4$ @ 1.0 % (T_8; 1.58 %).

The higher sugar accumulation under B and K treatments may be associated with their roles in carbohydrate metabolism. Boron application has been reported to enhance sucrose accumulation by upregulating sucrose phosphate synthase (SPS) and suppressing acidic β-fructofuranosidase expression during strawberry fruit development (Yu et al. 2024). Similarly, potassium promotes carbohydrate metabolism and translocation of photoassimilates from source leaves to developing fruits. It also influences enzymes involved in sucrose metabolism, including sucrose phosphate synthase and sucrose synthase (SUS), while enhancing photosynthesis and phloem transport of sugars (Berg et al. 2009; Philippar et al. 2003). Consequently, adequate K nutrition can promote sugar accumulation and improve fruit quality. Similar increases in soluble sugars following K application have been reported in citrus, grapes, apple and pear (Obenland et al. 2015; Zhang et al. 2018; Shen et al. 2017).

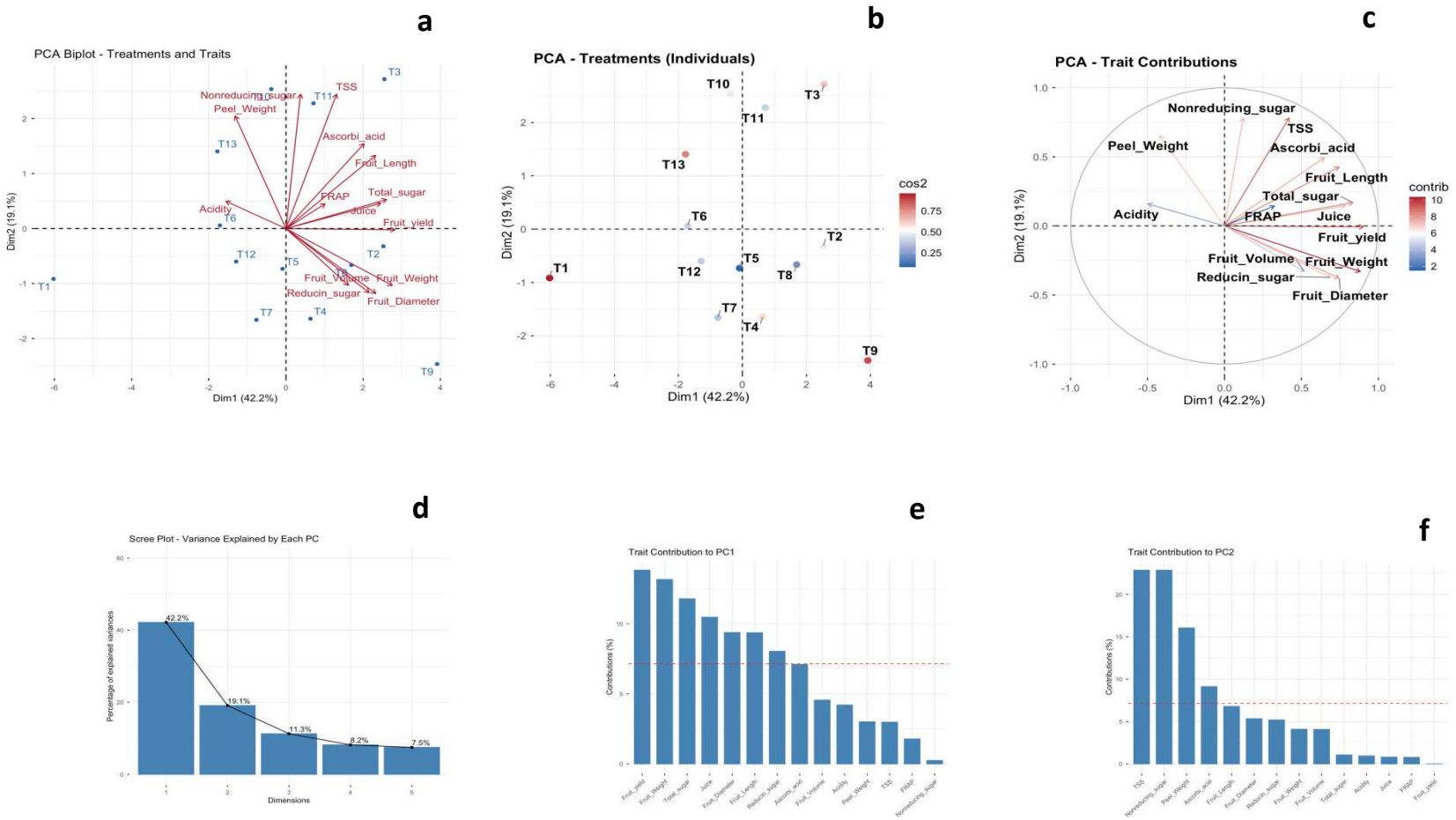
Marked variation was observed in FRAP activity among the treatments, with values ranging from 11.04 to 15.58 µmol TE/g FW. The highest FRAP activity was recorded with K_2SO_4 @ 1.0 % (T_3; 15.58 µmol TE/g FW), followed by K_2SO_4 @ 0.5 % (T2; 15.03 µmol TE/g FW). The higher antioxident activity under K_2SO_4 application is consistent with the findings of Zareei et al. (2018), who reported a concentration-dependent increase in antioxidant activity with K_2SO_4 application in grapes. Similar potassium-associated enhancement of antioxidant activity has also been reported in pomegranate and pineapple (Tehranifar and Tabar, 2009; Soares et al. 2005). This increase may be associated with enhanced accumulation of phenolic compounds, which contribute to antioxidant activity through their free-radical scavenging ability. Zareei et al. (2018) suggested that K_2SO_4 induced enhancement of carbohydrate accumulation may indirectly promote phenolic compound synthesis. Although this relationship could not be evaluated through correlation analysis in the present study due to the unavailability of corresponding data, previous studies have reported a positive association between phenolic compounds, anthocyanins and antioxidant

activity (Wang and Lin, 2000; Gómez-Plaza et al. 2006; Orak, 2007). Thus, the enhanced FRAP activity with K_2SO_4 may be partly attributed to its possible influence on phenolic compound accumulation.

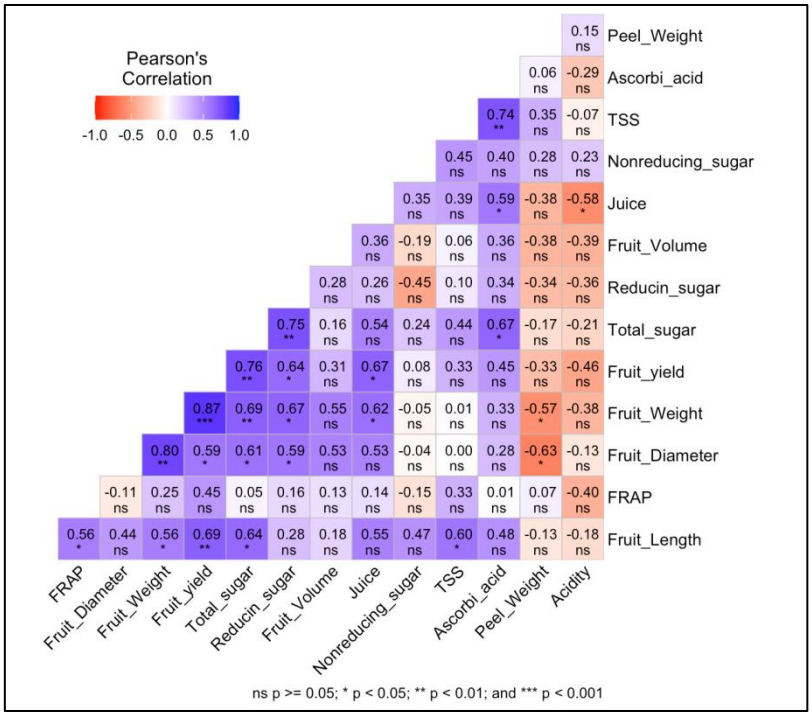
Multivariate analysis

Multivariate analysis was performed to assess variability and interrelationships among yield and quality traits and to identify the major contributors to total variation (Legua et al. 2014; Bala et al. 2025; Akshay et al. 2026). PCA is widely used to reduce data complexity and identify similarities and differences among treatments based on multiple variables (Shaw et al., 2001). In the present study, PC1 and PC2 explained 61.3 % of the total variance (Fig.3), with PC1 mainly associated with fruit size and yield traits, while PC2 was influenced by TSS, non-reducing sugar, peel weight, and ascorbic acid. This highlights the importance of both morpho-physical and biochemical traits in explaining treatment variability. Similar traits, including juice content, fruit size, TSS, sugars, ascorbic acid, and peel characteristics, have been reported as important determinants of fruit value and consumer acceptability (Singh et al. 2025). T_9 ($ZnSO_4$ @ 2.0 %) was mainly associated with superior fruit size and yield, whereas T_3 ($K2SO_4$ @ 1.0 %) showed a favorable combination of yield, size, and sugar traits, indicating its balanced performance. In contrast, T_1 (Control) showed the lowest overall trait values.

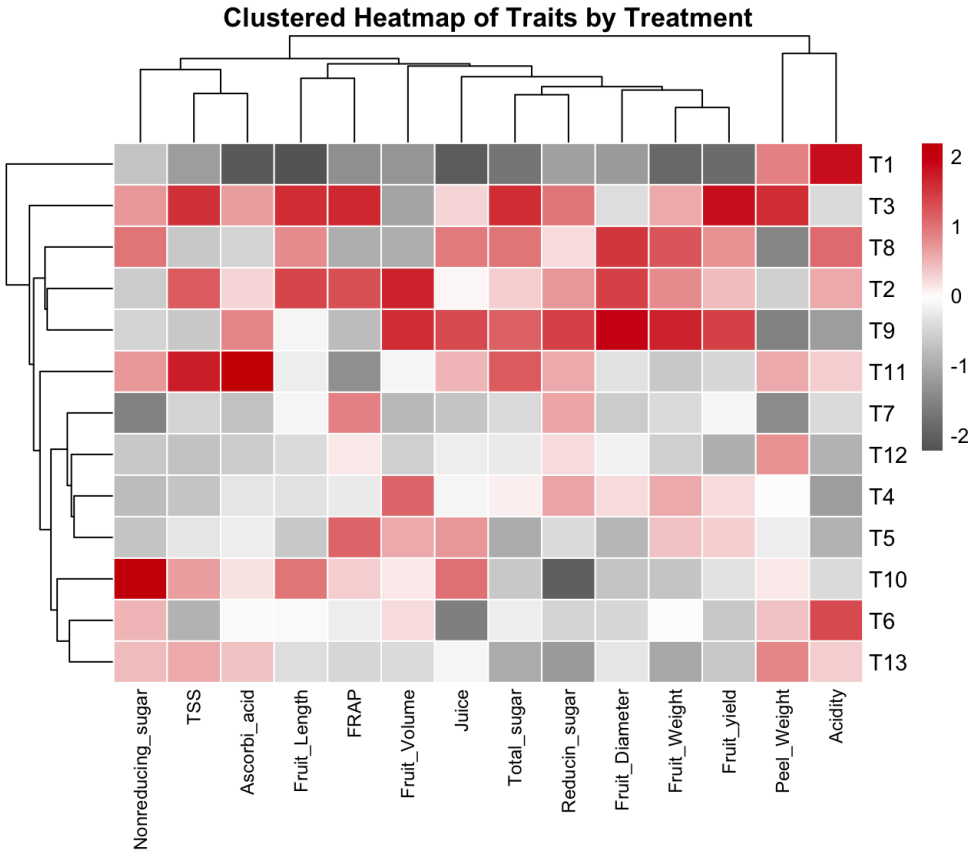
Pearson's correlation analysis further revealed strong relationships among fruit size, yield, and quality traits (Fig. 4). Fruit diameter was strongly correlated with fruit weight ($r = 0.80$, $p < 0.01$), while fruit weight showed a highly significant association with fruit yield ($r = 0.87$, $p < 0.001$), indicating that coordinated fruit enlargement contributes to higher productivity (Pandey et al. 2026; Chavda et al. 2026; Bala et al. 2025). Positive associations of fruit weight and yield with total and reducing sugars suggest greater carbohydrate accumulation in larger fruits, possibly due to greater sink capacity (Bala et al. 2025). TSS also showed a strong positive correlation with ascorbic acid ($r = 0.74$, $p < 0.01$), supporting their concurrent accumulation during fruit maturation (Vavoura et al. 2022). Conversely, juice content was negatively correlated with acidity ($r = -0.58$, $p < 0.05$), reflecting the typical sugar-acid balance during ripening (Vavoura et al. 2022). Fruit diameter also showed a significant negative correlation with peel weight ($r = -0.63$, $p < 0.05$), suggesting a possible trade-off between fruit enlargement and peel biomass that may influence juice recovery (Tadeo et al. 2020; Anticona et al. 2022).



374 **Fig. 3** PCA analysis of fruit morpho-pomological and biochemical traits across treatments (T_1–T_{13}): (a) biplot, (b) individual plot, and (c) trait
375 correlation circle, showing distribution of traits and treatments along PC1 and PC2 (61.3 % total variation). (d) Scree plot of variance explained
376 per component. (e, f) Trait contributions (%) to PC1 and PC2, respectively.



377 **Fig. 4 P**earson's correlation coefficients for the studied fruit physico-chemical traits
378 along with the derived indices. Positive correlations are depicted in shades of blue,
379 while negative correlations are shown in shades of red. Significance levels were as
380 follows: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.



381 **Fig. 5** Agglomerative Hierarchical Clustering (AHC) depicting the relationship
382 among the studied treatments studied.

Agglomerative hierarchical clustering (AHC) progressively groups treatments and traits according to similarity of their performance (Ran et al. 2023). The heatmap analysis integrated all traits and provided clear treatment-wise comparisons. T_3 (K_2SO_4 @ 1.0 %), T_8 ($ZnSO_4$ @ 1.0 %), T_2 (K_2SO_4 @ 0.5 %), and T_9 ($ZnSO_4$ @ 2.0 %) formed a major cluster with high fruit weight, yield, diameter, and total sugar, supporting the PCA and correlation results (Fig. 5). T_{11} (H_3BO_3 @ 1.0 %) formed a separate cluster characterized by high ascorbic acid, TSS, and fruit length, indicating greater influence on biochemical quality. T_1 (Control) consistently showed low trait expression, confirming its inferior performance. The clustering of fruit weight, yield, and diameter, and the separate grouping of acidity and peel weight, also corresponded with the correlation patterns (Fig. 5). Similar agreement among AHC, PCA, and correlation analysis has been reported in citrus studies [de Carvalho et al. 2019; Ran et al. 2023). Overall, the multivariate analyses consistently identified treatments with superior combined yield and fruit quality.

Conclusion

Foliar nutrient application significantly improved morpho-pomological, yield, and biochemical attributes, and antioxidant activity compared with the control. Among the different treatments given K_2SO_4 @ 1.0 % (T_3) showed the best overall performance, while $ZnSO_4$ @ 2.0 % (T_9) and H_3BO @ 1.0% (T11) were particularly effective for specific yield and quality traits. Multivariate analyses further supported the superior performance of these treatments and revealed strong interrelationships among fruit size, yield, and quality attributes. However, a single nutrient treatment should not be considered a definitive recommendation, as fruit development and quality are governed by complex interactions among multiple nutrients and metabolic pathways. Future studies integrating molecular-level investigations with advanced metabolomics and multi-omics approaches could provide more comprehensive and reliable insights for optimizing nutrient combinations and developing precise nutrient management strategies.

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Author contributions

Ladup Lepcha: Methodology, statistical analysis and writing original draft, Abu Hasan: Conceptualization, supervision and editing final draft, Prakriti Debnath: Methodology

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Data Availability

The data used in this article will be made available upon request to the corresponding author.

Declarations

Competing interests The authors declare that there are no conflicts of interest related to this work.

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626 **Table 2** Effect of nutrient spray on morpho-pomological and biochemical parameters of Malta

Treatment	Fruit Weight (g)	Fruit Length (cm)	Fruit Diameter (cm)	Fruit Volume (cm^3)	Peel Weight (g)	Juice %	TSS (°Brix)	Acidity (%)	Ascorbic acid (mg 100 ml^{-1})	Total sugar (%)	Reducing sugar (%)	Non-reducing sugar (%)	FRAP (µmol TE g^{-1} FW)	Fruit yield (kg $tree^{-1}$)
T1	186.63^{h}	6.73^{b}	6.93^{b}	146.0^{h}	40.49^{b}	37.20^{g}	8.01^{e}	0.31^{a}	41.50^{e}	3.87^{f}	2.64^{ef}	1.16^{cd}	11.04^{e}	12.46^{i}
T2	204.16^{bc}	7.56^{a}	7.47^{ab}	167.05^{a}	33.24^{e}	43.60^{de}	9.83^{ab}	0.26^{bc}	46.09^{bcd}	4.60^{bc}	3.36^{ab}	1.18^{bcd}	15.03^{ab}	15.31^{cd}
T3	202.8^{c}	7.61^{a}	7.10^{ab}	147.02^{gh}	44.23^{a}	44.23^{cde}	10.10^{a}	0.22^{cd}	46.85^{bc}	5.05^{a}	3.45^{ab}	1.52^{abc}	15.58^{a}	17.04^{a}
T4	202.75^{c}	7.16^{ab}	7.22^{ab}	163.00^{ab}	36.07^{cde}	42.99^{def}	8.39^{de}	0.19^{d}	45.00^{bcd}	4.51^{cd}	3.31^{abc}	1.13^{cd}	12.71$^{a..e}$	14.99^{de}
T5	201.66^{cd}	7.09^{ab}	7.00^{ab}	159.00^{bc}	35.16^{de}	45.57^{abc}	8.70^{d}	0.20^{d}	45.16^{bcd}	4.12^{ef}	2.90^{cde}	1.16^{cd}	14.79^{abc}	15.13^{d}
T6	198.92^{de}	7.22^{ab}	7.08^{ab}	156.67^{cd}	38.18^{bcd}	38.66^{g}	8.22^{de}	0.29^{ab}	45.43^{bcd}	4.41^{cde}	2.87^{de}	1.46^{bc}	12.73$^{a..e}$	13.90^{gh}
T7	195.99^{ef}	7.21^{ab}	7.05^{ab}	149.00^{fgh}	29.21^{f}	41.36^{f}	8.53^{d}	0.22^{cd}	44.13^{d}	4.32^{cde}	3.32^{abc}	0.95^{d}	14.42$^{a..d}$	14.60^{ef}
T8	206.94^{b}	7.43^{a}	7.48^{ab}	148.00^{gh}	28.78^{f}	46.23^{ab}	8.40^{de}	0.28^{ab}	44.55^{cd}	4.84^{ab}	3.17^{bcd}	1.58^{ab}	11.63^{de}	15.64^{c}
T9	209.97^{a}	7.21^{ab}	7.58^{a}	166.33^{a}	28.48^{f}	47.43^{a}	8.40^{de}	0.19^{d}	47.19^{b}	4.89^{ab}	3.62^{a}	1.20^{bcd}	11.04^{e}	16.51^{b}
T10	194.36^{fg}	7.47^{a}	7.04^{ab}	156.00^{cde}	36.76^{cd}	46.40^{ab}	9.44^{bc}	0.22^{cd}	45.87^{bcd}	4.25^{de}	2.29^{f}	1.87^{a}	13.54$^{a..e}$	14.30^{fg}
T11	194.82^{fg}	7.19^{ab}	7.11^{ab}	154.00^{cdef}	39.08 bc	44.81^{bcd}	10.23^{a}	0.25^{bc}	49.78^{a}	4.91^{a}	3.30^{abc}	1.52^{abc}	11.88^{bc}	14.16^{fg}
T12	195.28^{fg}	7.14^{ab}	7.14^{ab}	151.00^{efgh}	40.01^{b}	42.75^{ef}	8.33^{de}	0.20^{d}	44.33^{d}	4.39^{cde}	3.16^{bcd}	1.17^{bcd}	13.29$^{a..e}$	13.53^{h}
T13	192.25^{g}	7.15^{ab}	7.12^{ab}	152.00^{defg}	40.29^{b}	43.03^{def}	9.35^{c}	0.25^{bc}	46.30^{bcd}	4.12^{ef}	2.60^{ef}	1.45^{bc}	12.38$^{b..e}$	13.92^{gh}
SE (±)	**1.02**	**0.19**	**0.18**	**1.61**	**0.97**	**0.59**	**0.15**	**0.014**	**0.74**	**0.1**	**0.13**	**0.12**	**1.07**	**0.15**
CV (%)	**0.89**	**4.54**	**4.29**	**1.8**	**4.64**	**2.37**	**2.84**	**10.09**	**2.8**	**3.68**	**7.43**	**16.16**	**14.21**	**1.75**
LSD (p ≤ 0.05)	**2.97**	**0.55**	**0.52**	**4.71**	**2.82**	**1.73**	**0.43**	**0.04**	**2.15**	**0.28**	**0.39**	**0.36**	**3.13**	**0.44**
Range	**186.61 – 209.97**	**6.73 – 7.61**	**6.93 – 7.58**	**146.00 – 167.00**	**28.48 – 44.23**	**37.20 – 47.43**	**8.01 – 10.23**	**0.19 – 0.31**	**40.17 – 50.12**	**3.87 – 5.14**	**2.07 – 3.75**	**0.95 – 1.87**	**11.04–15.58**	**12.46 – 17.04**

627 *different letters indicate significant differences at $p \leq 0.0$

628

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