



## Effects of Calcium and Magnesium Application on Yield and Fruit Quality of Oranges in Thanh Hoa Province, Vietnam

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### Abstract

Calcium (Ca) and magnesium (Mg) are essential secondary macronutrients that govern plant growth, fruit development, and physiological stability of citrus production. Specifically, these elements play a crucial role in mitigating fruit cracking and enhancing fruit quality. The objective of the study was to determine the optimal application rates of Ca and Mg to maximize yield and fruit quality of Xa Doai oranges in Thanh Hoa Province, Vietnam. The experiment was conducted from December 2024 to December 2025 on seven-year-old Xa Doai orange trees, using a randomized complete block design and 3 replications. Treatments consisted of 3 levels of Ca (2.0, 2.5, and 3.0 kg tree<sup>-1</sup>) and Mg (0.5, 1.0, and 1.5 kg tree<sup>-1</sup>). The results showed that the application of 3.0 kg CaSO<sub>4</sub>·2H<sub>2</sub>O and 1.5 kg MgSO<sub>4</sub>·7H<sub>2</sub>O were effective in improving soil pH (6.35) and resulted in high exchangeable Ca and Mg (1,012.60 and 188.33 mg kg<sup>-1</sup>, respectively) and the lowest level of fruit cracking (10.82%). Conversely, the highest yield (50.84 kg tree<sup>-1</sup>), total soluble solids (TSS, 11.53%), and TSS/TA ratio (25.61) were obtained with the lower application rates of 2.0 kg CaSO<sub>4</sub>·2H<sub>2</sub>O mixed with 0.5 kg MgSO<sub>4</sub>·7H<sub>2</sub>O. Analysis results indicated that the exchangeable Ca in soil was negatively correlated with fruit weight ( $r = -0.77$ ), fruit circumference ( $r = -0.70$ ), fruit cracking ( $r = -0.90$ ), TSS ( $r = -0.75$ ), and TSS/TA ratio ( $r = -0.94$ ), but positively correlated with peel thickness ( $r = 0.88$ ). The results offer a viable basis for maximizing fertilization in the production of oranges.

**Keywords:** Ferralsol soil; fruit cracking; nutrient management; secondary macronutrients; Xa Doai orange

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### INTRODUCTION

The orange (*Citrus sinensis* L. Osbeck) is among the most economically valuable fruit crops cultivated in Vietnam and globally. In 2024, the total area of orange production in the country was 71,391 ha, with an average production of more than 26 tons ha<sup>-1</sup>. Nonetheless, this has recently exhibited a downward trend, declining by 807 ha relative to 2023 (FAO, 2026). The Xa Doai orange is one of the domestic varieties that are highly appreciated for its

thin peel, bright yellow flesh, high juiciness, crisp texture, and unique sweet flavor. Although the Xa Doai orange is a premium product, its cultivation area and fruit productivity have decreased over the past few years, accompanied by significant degradations in fruit quality. Such tendencies are usually attributed to conventional cultivation methods, the loss of soil fertility, and the ineffective use of nutrients (Hien et al., 2026b).

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Nutrient management is a pivotal factor in citrus productivity and fruit quality. Although primary macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are well known, the secondary macronutrients, especially calcium (Ca) and magnesium (Mg), are equally important (Lima Neto et al., 2025). Ca plays a crucial role in the structure of cell walls, the increase of fruit firmness, and the control of physiological processes associated with fruit quality (Jain et al., 2019; Wu et al., 2023; Chen et al., 2024). Furthermore, Mg, a core constituent of chlorophyll, directly promotes photosynthesis and helps in the total soluble solids (TSS) accumulation (Tian et al., 2023). Ca and Mg deficiencies or imbalances have been commonly reported in the orange-growing areas in Nghe An, particularly in oranges planted on Ferralsol soil (Hien and Toan, 2020). These conditions often result in stunted tree growth and a high susceptibility to fruit cracking and premature abscission, particularly during periods of irregular rainfall.

Fruit cracking remains a critical constraint in citrus production, leading to a substantial decrease in marketable yield. Reported cracking rates can reach 48.2 to 50.6% in the post-physiological fruit drop stage, especially in years with an uneven distribution of rainfall (Hien et al., 2017; Shi et al., 2025). The phenomenon is highly dependent on soil properties and nutrient status; specifically, Ca and Mg are recognized as the main factors that contribute to it, along with soil texture and P availability (Shi et al., 2025). Previous studies have demonstrated that these problems can be alleviated through Ca and Mg supplementation. For instance, foliar application of  $\text{CaCl}_2$  at concentrations of 1 to 1.5% has been reported to enhance fruit size, weight, and pulp yield by increasing pectin and cytokinin concentrations (Aly et al., 2015; Khalaj et al., 2017; Ali et al., 2021). In particular, foliar and soil application of Ca salts enhances fruit firmness, size, and cracking resistance, increasing pectin cross-linking and cell wall stability (Aly et al., 2015; Zhang et al., 2019; Dong et al., 2025). Likewise, Mg levels of 142 to 177 g tree<sup>-1</sup> have been reported to enhance yield and economic profitability (Bonomelli et al., 2022; Liu et al., 2022).

Orange production in Thanh Hoa Province has grown substantially over the past few years; however, the literature on site-specific nutrient management, especially the interactive impacts of Ca and Mg within local pedoclimatic (soil and climate) conditions, is scant. This knowledge gap

limits the formulation of effective fertilization practices to suit Xa Doai orange production. Sealing this gap is crucial not only for enhancing yield and fruit quality but also for improving fertilizer efficiency, reducing input costs, and supporting sustainable production systems.

Therefore, the purpose of the study is to assess the impact of different rates of soil applications of gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ) and magnesium sulfate ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ) on the chemical properties of soil, fruit yield components, the occurrence of fruit cracking, and the parameters of juice quality of the orange trees of the Xa Doai species. The results are expected to provide a scientific basis for optimizing fertilization strategies, production efficiency, and long-term sustainability of orange farming in the area.

## MATERIALS AND METHOD

### Research location and materials

The experiment was conducted from December 2024 to December 2025 using Xa Doai orange trees grafted onto sour pummelo rootstock (*Citrus grandis* L. Osbeck). This premium type is extensively cultivated in Nghe An, Ha Tinh, and some provinces in northern Vietnam. The experimental orchard was established in 2017, and the trees had reached 7 years at the commencement of the study.

The study was conducted in Xuan Binh commune, Thanh Hoa Province (105°41' E, 19°47' N). The soil is classified as a Ferralsol with a texture of 21.0% sand, 27.0% silt, and 52.0% clay. The soil concentrations of Zn, Mn, B, and Fe were 1.81, 8.52, 0.35, and 37.51 mg kg<sup>-1</sup>, respectively. Other soil chemical properties are presented in Table 2. The local climate is characterized as tropical monsoon with an average rainfall of 1,600 to 2,000 mm year<sup>-1</sup>, a mean temperature ranging from 15 to 35 °C, and a relative humidity of 75 to 90%.

Ca and Mg were supplied in the form of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  and  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ , respectively. Phu My urea (46% N), potassium chloride (60% K<sub>2</sub>O), Van Dien phosphate (15% P<sub>2</sub>O<sub>5</sub>), and Que Lam composted cow manure (22% organic matter, C/N ratio of 11, 3% total N, 4% humic acid, and 25% moisture content) were used as basal fertilizers.

### Experimental design and treatments

The experiment was performed in a randomized complete block design (RCBD) consisting of 9 treatments, arranged in a factorial combination of 3 levels of  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  and

3 levels of  $MgSO_4 \cdot 7H_2O$  (Table 1). The planting density was 500 trees  $ha^{-1}$  (spacing 4 m  $\times$  5 m). Each treatment was replicated 3 times with 5 trees per replication, making a total of 135 trees in an experimental area of 2,700  $m^2$ . Standard local agronomic practices were strictly maintained throughout the experimental period, including canopy pruning, manual and chemical weed control, and integrated pest management (IPM). The orange orchard utilized a drip irrigation system with a flow rate of 12 liters per hour per tree. Irrigation was applied in April, May, June, and July, averaging 4 irrigations per month, with each session lasting 2 hours.

Besides the experimental treatments, all trees were basal-fertilized as per the common local practice, i.e., 40 kg  $tree^{-1}$  Que Lam composted cow manure; 0.4 kg  $P_2O_5$   $tree^{-1}$ ; 250 g N  $tree^{-1}$ ; 120 g  $K_2O$   $tree^{-1}$ . Fertilizer application was divided into 5 distinct phases. The initial application (post-harvest, January 2025) contained 100%  $CaSO_4 \cdot 2H_2O$  and  $MgSO_4 \cdot 7H_2O$ . The second application, which took place 15 days later, provided 30% N, 20%  $K_2O$ , 100%  $P_2O_5$ , and 100% organic matter. The third (May 2025) and fourth (August 2025) applications contained 40% N and 30%  $K_2O$ , respectively. The last application (October 2025) was about fruit maturation and provided a remaining 20%  $K_2O$ .

#### Soil sampling and analysis

Soil sampling was performed twice: once before fertilizer application (December 2024) and once after fertilizer application (December 2025). The experimental replicates yielded 27 soil samples. Each sample consisted of 4 subsamples collected using sampling tubes from positions beneath the tree canopy at depths of 0 to 20 cm. The subsamples were mixed, well homogenized, dried in the air under laboratory conditions, and sieved through a 2 mm mesh before analysis.

Table 1. Ca and Mg application rates for each treatment

Treatment	$CaSO_4 \cdot 2H_2O$ (kg $tree^{-1}$ )	$MgSO_4 \cdot 7H_2O$ (kg $tree^{-1}$ )
T <sub>1</sub>	2.0	0.5
T <sub>2</sub>	2.0	1.0
T <sub>3</sub>	2.0	1.5
T <sub>4</sub>	2.5	0.5
T <sub>5</sub>	2.5	1.0
T <sub>6</sub>	2.5	1.5
T <sub>7</sub>	3.0	0.5
T <sub>8</sub>	3.0	1.0
T <sub>9</sub>	3.0	1.5

The chemical properties of the soil were determined using standard procedures. Soil pH was measured in a 1:2.5 soil-to-water suspension using a calibrated pH meter. At pH 7.0, exchangeable K, Ca, and Mg were extracted using 1 M  $NH_4OAc$ . Exchangeable K was measured by flame photometry, and exchangeable Ca and Mg were measured using an atomic absorption spectrometer. Extraction of the available P was done by adding 0.03 M  $NH_4F$  to 0.10 M HCl, and the P was quantified by the molybdenum blue method (Jones, 2001; 2003).

#### Fruit sampling and analysis

In December 2025, fruits were picked when physiologically mature. Standard procedures were used to measure all the measurements. The number of fruit was calculated by counting all marketable fruits at harvest. The average weight of fruits (g) was determined by taking 30 randomly chosen fruits per tree with the help of an electronic balance ( $\pm 0.01$  g). The circumference (cm) of the fruit was determined with an electronic caliper ( $\pm 0.01$  cm), on 3 fruits on each tree. The peel thickness (cm) was determined at 4 points equally spaced around the fruit equator with the same caliper, and 3 fruits per tree were used to obtain mean values. The total fresh weight of harvested fruits on a handheld electronic scale was used to determine fruit yield per tree (kg). The rate of cracking of fruits was calculated as the percentage of cracked fruits divided by the total number of fruits multiplied by 100.

Juice ratio (as a percentage of weight) was calculated by juicing sampled fruits in a stainless-steel juicer. The juice was filtered and weighed, then calculated using Equation 1.

$$\text{Juice ratio (\%)} = \frac{\text{Juice weight}}{\text{Fruit weight}} \times 100 \quad (1)$$

Total soluble solids (TSS) were measured using a digital refractometer (ATAGO PAL-1, Japan) at 20 °C. The titratable acidity (TA, % citric acid) was calculated by titration of 10 ml of filtered juice (diluted with 50 ml of distilled water) with 0.1 N NaOH in the presence of phenolphthalein as an indicator (Boland, 1995). TA was determined using Equation 2.

$$\text{TA (\% citric acid)} = \frac{\text{Volume of NaOH} \times \text{Normality} \times 0.064}{\text{Volume of juice}} \times 100 \quad (2)$$

Where 0.064 is the milliequivalent weight of citric acid.

The amount of vitamin C ( $\text{mg l}^{-1}$ ) was determined by the use of the 2,6-dichlorophenolindophenol (DCPIP) dye titration method. Ten milliliters of juice were titrated with standard DCPIP solution to a persistent pink color, and concentration was determined using a standard ascorbic acid curve.

### Data analysis

Data visualization and exploratory statistical analyses were performed using R software version 4.5.3 within RStudio. Data normality was evaluated prior to further statistical analysis to assess the suitability of parametric procedures. Pearson correlation analysis was performed to investigate linear associations among the measured variables. The tidyverse package was used for data organization and management, whereas graphical outputs were generated using the ggplot2 package. Continuous variables were visualized as bar charts showing treatment means, with error bars representing the standard deviation (SD). To enhance data transparency, individual raw data points from all 9 replicates per treatment were overlaid on the bars using jittered scatter plots. Multivariate relationships among variables were examined using principal component analysis (PCA) with the FactoMineR and factoextra packages. Before PCA, variables were standardized to unit variance to account for differences in measurement scales.

## RESULTS AND DISCUSSION

### Soil properties

The results of the soil chemical analysis, both prior to and following fertilization, are presented in Figure 1 and Table 2. There was no significant difference in soil pH at the beginning of the treatments. However, following the application of Ca and Mg, soil pH increased significantly, ranging from 5.67 to 6.35. The maximum pH (6.35) was observed in the treatment that applied

3.0 kg of Ca and 1.5 kg of Mg, which was significantly higher than in treatments with lower Ca application rates. These values are within the ideal pH range for orange growing (5.5 to 6.5) as reported by Hien and Toan (2020). Root development is also improved at this pH, but too high a pH (e.g., 8.5) has been found to inhibit root growth and nutrient uptake (Sambani et al., 2025). Two-way analysis of variance (ANOVA) revealed that Ca and Mg fertilization significantly affected soil pH. The effects of Ca and Mg were particularly strong, with  $F$ -values of 4.120 and  $p = 0.021$ , indicating a pronounced response of soil pH to fertilization. The application of fertilizers containing Ca and Mg reduced  $\text{Al}^{3+}$  mobility, thereby increasing soil pH and cation exchange capacity (Regasa et al., 2025; Zhang et al., 2025).

There was no significant difference in available P content before and after fertilization, with values ranging from 13.50 to 16.70  $\text{mg kg}^{-1}$ . However, there was a slight upward trend with increasing rates of Ca and Mg application, suggesting enhanced P availability. This trend aligns with Wadu et al. (2013), who indicated that Mg inhibits Ca and P precipitation, thus increasing P availability in soils with low Ca/Mg saturation.

There was no significant difference in exchangeable K among treatments prior to fertilization. Following fertilization, however, K concentrations decreased to 98.30 to 117.50  $\text{mg kg}^{-1}$ , exhibiting an inverse relationship with the application rates of Ca and Mg. The minimum K content (98.30  $\text{mg kg}^{-1}$ ) was recorded when 3.0 kg of Ca and 1.5 kg of Mg were used together. The ANOVA results showed that the exchangeable K after the experiment differed significantly by Ca, Mg, and the Ca  $\times$  Mg interaction, with  $p$ -values of 0.025, 0.048, and 0.019, respectively. This decline could be attributed to cation antagonism within the soil matrix; elevated levels

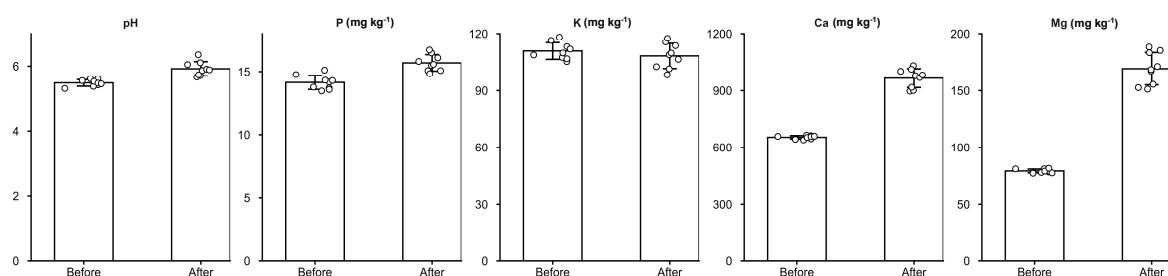


Figure 1. Effects of Ca and Mg fertilization on the soil chemical properties

Note: Bar height represents the mean value; error bars indicate the standard SD. Individual black dots represent scatter data from 9 distinct samples per indicator

Table 2. Effect of Ca and Mg application on soil chemical properties before and after fertilization

Treatment	pH		Available P (mg kg <sup>-1</sup> )		Exchangeable K (mg kg <sup>-1</sup> )		Exchangeable Ca (mg kg <sup>-1</sup> )		Exchangeable Mg (mg kg <sup>-1</sup> )	
	Before	After	Before	After	Before	After	Before	After	Before	After
T1	5.32 <sup>a</sup>	5.67 <sup>b</sup>	14.80 <sup>a</sup>	15.10 <sup>a</sup>	108.83 <sup>a</sup>	115.70 <sup>ab</sup>	658.32 <sup>a</sup>	897.30 <sup>c</sup>	81.30 <sup>a</sup>	151.30 <sup>b</sup>
T2	5.61 <sup>a</sup>	5.71 <sup>b</sup>	13.73 <sup>a</sup>	15.53 <sup>a</sup>	105.33 <sup>a</sup>	108.90 <sup>abc</sup>	661.60 <sup>a</sup>	901.20 <sup>c</sup>	78.60 <sup>a</sup>	167.20 <sup>ab</sup>
T3	5.43 <sup>a</sup>	5.73 <sup>b</sup>	14.20 <sup>a</sup>	14.80 <sup>a</sup>	113.22 <sup>a</sup>	117.50 <sup>a</sup>	645.33 <sup>a</sup>	917.30 <sup>c</sup>	79.20 <sup>a</sup>	183.23 <sup>a</sup>
T4	5.38 <sup>a</sup>	5.87 <sup>ab</sup>	15.10 <sup>a</sup>	15.60 <sup>a</sup>	107.50 <sup>a</sup>	109.80 <sup>abc</sup>	663.70 <sup>a</sup>	978.50 <sup>b</sup>	81.33 <sup>a</sup>	155.61 <sup>b</sup>
T5	5.56 <sup>a</sup>	5.91 <sup>ab</sup>	13.80 <sup>a</sup>	16.13 <sup>a</sup>	116.50 <sup>a</sup>	113.70 <sup>ab</sup>	642.80 <sup>a</sup>	968.80 <sup>b</sup>	77.53 <sup>a</sup>	171.20 <sup>ab</sup>
T6	5.62 <sup>a</sup>	5.89 <sup>ab</sup>	13.50 <sup>a</sup>	15.10 <sup>a</sup>	118.20 <sup>a</sup>	106.50 <sup>bcd</sup>	639.40 <sup>a</sup>	982.33 <sup>b</sup>	78.22 <sup>a</sup>	185.33 <sup>a</sup>
T7	5.53 <sup>a</sup>	6.05 <sup>ab</sup>	14.30 <sup>a</sup>	15.80 <sup>a</sup>	109.80 <sup>a</sup>	102.60 <sup>cd</sup>	652.30 <sup>a</sup>	1,001.50 <sup>a</sup>	79.30 <sup>a</sup>	152.63 <sup>b</sup>
T8	5.48 <sup>a</sup>	6.11 <sup>ab</sup>	13.60 <sup>a</sup>	16.53 <sup>a</sup>	106.80 <sup>a</sup>	101.50 <sup>cd</sup>	656.70 <sup>a</sup>	1,031.60 <sup>a</sup>	81.80 <sup>a</sup>	168.53 <sup>ab</sup>
T9	5.46 <sup>a</sup>	6.35 <sup>a</sup>	14.30 <sup>a</sup>	16.70 <sup>a</sup>	111.90 <sup>a</sup>	98.30 <sup>d</sup>	658.92 <sup>a</sup>	1,012.60 <sup>a</sup>	77.80 <sup>a</sup>	188.33 <sup>a</sup>
Factors and their interaction										
Ca <i>F</i> -value ( <i>df</i> = 2)	1.120	2.350	0.730	1.630	0.350	3.110	1.060	11.560	1.530	5.480
Ca <i>p</i> -value	0.541	0.045	0.511	0.138	0.717	0.025	0.530	< 0.001	0.175	0.018
Mg <i>F</i> -value ( <i>df</i> = 2)	0.530	2.270	0.950	1.280	1.130	2.962	0.850	5.470	1.110	7.180
Mg <i>p</i> -value	0.612	0.048	0.180	0.271	0.476	0.048	0.126	0.016	0.215	0.001
Ca × Mg <i>F</i> -value ( <i>df</i> = 4)	0.920	4.120	0.580	1.760	1.230	3.140	0.930	10.120	1.280	4.320
Ca × Mg <i>p</i> -value	0.815	0.021	0.550	0.116	0.361	0.019	0.358	< 0.001	0.237	0.005

Note: Different letters within the same column indicate significant differences at  $p \leq 0.05$ . *F* and *p*-values were obtained from two-way ANOVA with Ca, Mg, and Ca × Mg as sources of variation. *p*-values lower than 0.001 are reported as < 0.001

of Ca and Mg can competitively inhibit the availability and uptake of K, potentially impacting fruit yield and quality (Hien et al., 2017; Yan et al., 2020; Yang et al., 2024).

There was no significant difference in exchangeable Ca content among treatments prior to fertilization. But a proportional increase in application rates post-fertilization with a range of 897.30 to 1,031.60 mg kg<sup>-1</sup>. Treatments involving 3.0 kg of Ca, regardless of the Mg level, yielded the highest exchangeable Ca concentrations, which were significantly greater than those in all other treatments. Notably, this was the only treatment group to reach the optimal threshold of citrus trees (Hien et al., 2016). Two-way ANOVA indicated that the exchangeable Ca after the experiment was significantly affected by Ca and the Ca × Mg interaction with  $p < 0.001$ , and was also affected by Mg with  $p = 0.016$ . These results indicate that the addition of Ca significantly increased the soil's exchangeable Ca content, while Mg may help regulate the cation balance. Li et al. (2020) also reported that applying Ca and Mg conditioners significantly increased soil exchangeable Ca compared with the control. Furthermore, maintaining adequate Ca concentrations is essential, as deficiency can impair root development and predispose trees to physiological disorders, such as fruit cracking (Shi et al., 2024).

Similarly, exchangeable Mg content showed no significant differences prior to fertilization but significant differences following application. The maximum Mg concentrations were consistently recorded at the 1.5 kg Mg rate across all Ca treatments and were significantly greater than those at the 0.5 kg Mg level. Despite these variations, the Mg concentration in all treatments remained within the optimal range of citrus production (120 to 240 mg kg<sup>-1</sup>; Hien et al., 2016). ANOVA showed that exchangeable Mg

after application was significantly influenced by Ca, Mg, and the Ca × Mg interaction, with  $p$ -values of 0.018, 0.001, and 0.005, respectively. This indicates that Mg fertilization is an important factor in increasing exchangeable Mg in the soil, but this effect also depends on its combination with Ca. This result is consistent with Li et al. (2025), who reported that additional fertilizers containing Mg increased exchangeable Mg content by 32.1% and increased wax gourd yield.

### Effects of Ca and Mg fertilization on yield components

The effects of Ca and Mg fertilization on the yield and its components are summarized in Figure 2 and Table 3. The number of fruits per tree in treatments ranged from 176.33 to 210.53. The maximum number of fruits was recorded in treatment 2.0 kg Ca and 0.5 kg Mg, which was notably higher than under other treatments. Interestingly, increasing Ca and Mg beyond these rates led to a reduction in fruit count. This implies that excessive Ca and Mg may have induced a nutrient imbalance, especially by suppressing K uptake, which is vital for fruit development. High Ca and Mg concentrations prevented K uptake in pummelo, thus inhibiting increases in fruit weight (Hien et al., 2017). Qu et al. (2023) also reported that excessive Mg fertilization inhibited plant K uptake. The results of the two-factor ANOVA showed that the number of fruits was not significantly affected by Ca or Mg alone, but was very significantly affected by the Ca × Mg interaction ( $F = 5.000$ ,  $p = 0.002$ ). This indicates that the number of fruits depends mainly on the combination of Ca and Mg rather than on the individual effects of each factor.

Fruit circumference remained relatively constant across most treatments, ranging from 6.50 to 7.83 cm. A significant reduction in fruit circumference was observed with an increase in

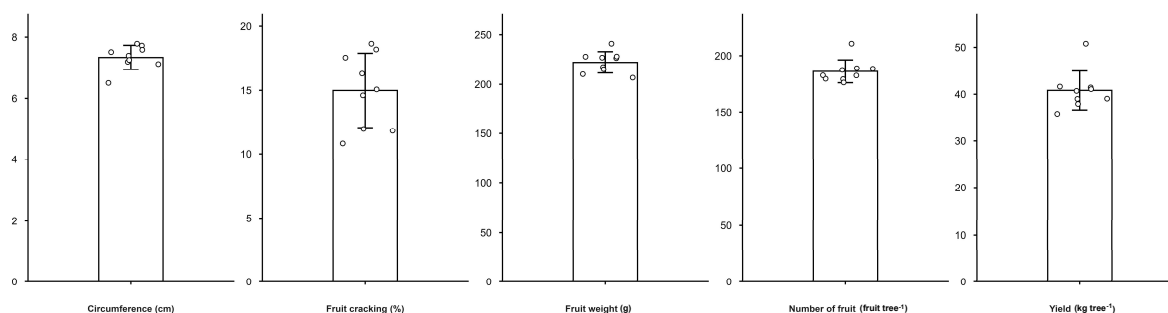


Figure 2. Effects of Ca and Mg fertilization on the yield components

Note: Bars show the mean values, while error bars represent the SD. The scatter points (black dots) illustrate the distribution of replicates for each yield parameter

Table 3. Effects of Ca and Mg fertilization on orange yield components

Treatment	Number of fruit (fruit tree <sup>-1</sup> )	Fruit cracking (%)	Fruit weight (g)	Circumference (cm)	Yield (kg tree <sup>-1</sup> )
T1	210.53 <sup>a</sup>	18.74 <sup>a</sup>	241.11 <sup>a</sup>	7.83 <sup>a</sup>	50.84 <sup>a</sup>
T2	179.52 <sup>b</sup>	17.50 <sup>ab</sup>	228.10 <sup>a</sup>	7.53 <sup>a</sup>	41.60 <sup>b</sup>
T3	182.40 <sup>b</sup>	18.10 <sup>ab</sup>	226.70 <sup>a</sup>	7.71 <sup>a</sup>	41.41 <sup>b</sup>
T4	187.50 <sup>b</sup>	16.33 <sup>bc</sup>	227.20 <sup>a</sup>	7.21 <sup>a</sup>	40.73 <sup>b</sup>
T5	189.00 <sup>b</sup>	15.11 <sup>c</sup>	228.33 <sup>a</sup>	7.60 <sup>a</sup>	41.11 <sup>b</sup>
T6	179.23 <sup>b</sup>	14.61 <sup>c</sup>	217.60 <sup>a</sup>	7.40 <sup>a</sup>	39.00 <sup>b</sup>
T7	176.33 <sup>b</sup>	12.10 <sup>d</sup>	215.50 <sup>a</sup>	7.30 <sup>a</sup>	38.00 <sup>b</sup>
T8	188.54 <sup>b</sup>	11.70 <sup>d</sup>	206.70 <sup>a</sup>	7.11 <sup>a</sup>	39.00 <sup>b</sup>
T9	182.61 <sup>b</sup>	10.82 <sup>d</sup>	210.30 <sup>a</sup>	6.50 <sup>a</sup>	35.84 <sup>b</sup>
Factors and their interaction					
Ca <i>F</i> -value ( <i>df</i> =2)	1.771	21.371	1.080	0.350	1.710
Ca <i>p</i> -value	0.182	< 0.001	0.349	0.177	0.193
Mg <i>F</i> -value ( <i>df</i> =2)	1.740	10.181	0.040	0.151	0.690
Mg <i>p</i> -value	0.188	< 0.001	0.959	0.466	0.506
Ca × Mg <i>F</i> -value ( <i>df</i> =4)	5.000	13.000	0.480	0.143	2.640
Ca × Mg <i>p</i> -value	0.002	< 0.001	0.748	0.574	0.046

Note: Different letters within the same column indicate significant differences at  $p \leq 0.05$ . *F* and *p*-values were obtained from two-way ANOVA with Ca, Mg, and Ca × Mg as sources of variation. *p*-values lower than 0.001 are reported as < 0.001

the application of Ca. A higher circumference was found in the 2.0 kg Ca and 0.5 kg Mg application. However, the ANOVA showed that applying Ca and Mg did not affect fruit circumference. Regarding yield, values ranged from 35.84 to 50.84 kg tree<sup>-1</sup>, with the highest yield observed with 2.0 kg Ca and 0.5 kg Mg applications, which was highly differentiated from all other treatments. Additional Ca and Mg did not improve the yield of oranges and, in fact, tended to reduce it. These results align with a study by Arrington and Vetter (2017), which showed that the rate of fruit set and yield in blueberries sprayed with Ca and B was not enhanced by Ca spraying. The ANOVA showed that yield was not significantly affected by Ca or Mg individually, but was affected by the Ca × Mg interaction ( $F = 2.640$ ,  $p = 0.046$ ). This indicates that yield responds to combined Ca and Mg fertilization.

The rate of fruit cracking varied greatly across treatments, ranging from 10.82 to 18.74%. This rate was greatly reduced as the amount of Ca applied increased. The highest fruit cracking was found in treatment 2.0 kg Ca combined with 0.5 kg Mg, which differed significantly from all other treatments. Two-way ANOVA indicated that the fruit cracking rate was influenced by Ca, Mg, and the interaction of Ca × Mg. Among these factors, Ca exhibited the most significant effect with  $F = 21.371$  and  $p < 0.001$ . The decrease in fruit cracking is mainly attributed to the effect of Ca in enhancing the structure of cell walls. Ca interacts with pectin to form calcium pectate, a primary constituent of the cell wall matrix. This process prevents degradation of the middle layer (gel layer) and increases structural integrity (Zhang et al., 2019). This mechanism is supported by previous studies. According to Dong et al. (2025), Ca fertilization was found to decrease fruit cracking by up to 71.09% by enhancing cell density and firmness, and also enhanced the

yield of oranges by 17.39%. Similarly, foliar application of a nutrient mixture of 0.20% CaCl<sub>2</sub> + 0.20% MgSO<sub>4</sub> + 0.20% FeSO<sub>4</sub> + 0.10% H<sub>3</sub>BO<sub>3</sub> reduced cracking rate by 59.27% in “Muscat Hamburg” and 70.49% in “Jumeigui” grape varieties (Zhang et al., 2023).

### Effects of Ca and Mg fertilization on fruit quality

The effects of Ca and Mg fertilization on the quality of fruits of Xa Doai oranges are presented in Figure 3 and Table 4. There was no significant difference in peel thickness between treatments, with a range of 0.32 to 0.51 cm. Two-way ANOVA indicated that peel thickness was not significantly influenced by Ca, Mg, or the Ca × Mg interaction. However, a slight upward trend with increased Ca and Mg rates. The same effects of Ca in enhancing peel thickness and firmness have been reported in other studies (Li et al., 2009; Dong et al., 2025). There were also no significant differences in juice ratio between treatments (56.9 to 61.4%).

There was significant variation in TSS among treatments, with a range of 9.83 to 11.53%. The highest TSS was observed under the application of 2.0 kg Ca and 0.5 kg Mg. Two-way ANOVA indicated that TSS was not significantly affected by Ca or Mg as independent variables; however, it was significantly affected by the Ca × Mg interaction with  $F = 3.510$ ,  $p = 0.014$ . This indicates that the change in TSS is not solely dependent on Ca or Mg, but rather on their combined effect. The decrease in exchangeable K observed in the soil (Table 2) may partially explain the decrease in TSS of the juice. Hien et al. (2017) also found that high Ca levels prevent pummelo uptake of K. Moreover, Ca may attenuate fruit respiration and metabolic activity, thereby delaying the conversion of polysaccharides into soluble sugars during

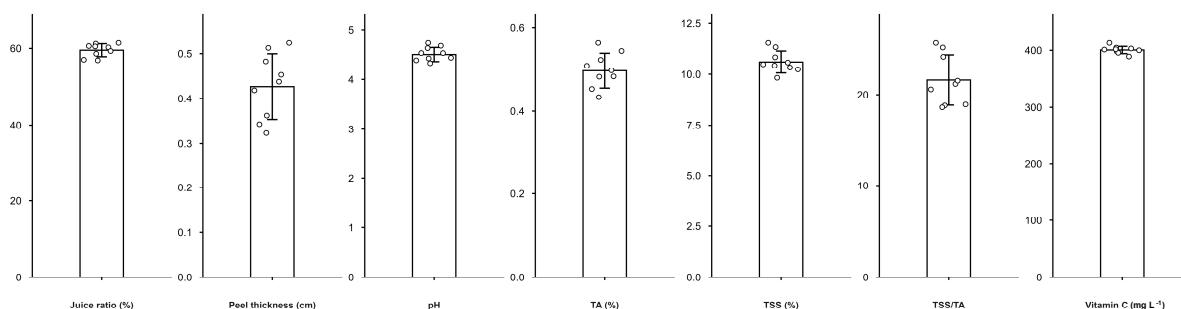


Figure 3. Effects of Ca and Mg fertilization on the quality components of oranges

Note: Data are presented as mean ± SD. Black scatter points reflect the raw data measurements, highlighting the shifts in soil chemical status before and after treatment

Table 4. Effects of Ca and Mg fertilization on the quality components of oranges

Treatment	Peel thickness (cm)	Juice ratio (%)	TSS (%)	pH	TA (%)	Vitamin C (mg l <sup>-1</sup> )	TSS/TA
T1	0.34 <sup>a</sup>	60.60 <sup>a</sup>	11.53 <sup>a</sup>	4.51 <sup>a</sup>	0.45 <sup>ab</sup>	412.51 <sup>a</sup>	25.61 <sup>a</sup>
T2	0.32 <sup>a</sup>	61.21 <sup>a</sup>	10.80 <sup>ab</sup>	4.70 <sup>a</sup>	0.43 <sup>b</sup>	404.20 <sup>a</sup>	25.10 <sup>ab</sup>
T3	0.36 <sup>a</sup>	58.63 <sup>a</sup>	11.30 <sup>ab</sup>	4.40 <sup>a</sup>	0.48 <sup>ab</sup>	397.90 <sup>a</sup>	24.10 <sup>abc</sup>
T4	0.42 <sup>a</sup>	57.11 <sup>a</sup>	10.51 <sup>c</sup>	4.42 <sup>a</sup>	0.51 <sup>ab</sup>	401.50 <sup>a</sup>	20.61 <sup>cd</sup>
T5	0.44 <sup>a</sup>	60.30 <sup>a</sup>	10.60 <sup>bc</sup>	4.71 <sup>a</sup>	0.50 <sup>ab</sup>	389.60 <sup>a</sup>	21.20 <sup>bcd</sup>
T6	0.45 <sup>a</sup>	59.30 <sup>a</sup>	10.32 <sup>c</sup>	4.50 <sup>a</sup>	0.48 <sup>ab</sup>	402.81 <sup>a</sup>	21.50 <sup>bcd</sup>
T7	0.51 <sup>a</sup>	56.90 <sup>a</sup>	9.83 <sup>c</sup>	4.32 <sup>a</sup>	0.52 <sup>ab</sup>	395.43 <sup>a</sup>	18.83 <sup>d</sup>
T8	0.48 <sup>a</sup>	60.50 <sup>a</sup>	10.40 <sup>c</sup>	4.61 <sup>a</sup>	0.56 <sup>a</sup>	401.50 <sup>a</sup>	18.63 <sup>d</sup>
T9	0.52 <sup>a</sup>	61.40 <sup>a</sup>	10.22 <sup>c</sup>	4.40 <sup>a</sup>	0.54 <sup>a</sup>	399.60 <sup>a</sup>	18.90 <sup>d</sup>
Factors and their interaction							
Ca <i>F</i> -value ( <i>df</i> =2)	0.700	0.890	0.510	1.120	0.210	0.540	0.140
Ca <i>p</i> -value	0.504	0.418	0.606	0.334	0.813	0.589	0.871
Mg <i>F</i> -value ( <i>df</i> =2)	0.900	0.020	2.490	0.440	3.380	0.490	5.860
Mg <i>p</i> -value	0.414	0.983	0.094	0.649	0.043	0.614	0.005
Ca × Mg <i>F</i> -value ( <i>df</i> =4)	0.270	0.380	3.510	0.178	3.390	1.360	5.480
Ca × Mg <i>p</i> -value	0.896	0.820	0.014	0.150	0.017	0.265	0.001

Note: Different letters within the same column indicate significant differences at  $p \leq 0.05$ . *F* and *p*-values were obtained from two-way ANOVA with Ca, Mg, and Ca × Mg as sources of variation. *p*-values lower than 0.001 are reported as < 0.001

ripening (Dorostkar et al., 2022). A similar decrease in TSS after  $\text{CaCl}_2$  application was also observed in figs (Souza et al., 2023).

There were no significant differences in juice pH and vitamin C content among the treatments. Total TA content ranged from 0.43 to 0.56%. The lowest TA content was found at 2.0 kg of Ca + 1.0 kg of Mg, and higher at 3.0 kg of Ca + 1.0 kg of Mg and 3.0 kg of Ca + 1.5 kg of Mg. Two-way ANOVA indicated that TA was not affected individually by Ca, but was affected by Mg and the Ca  $\times$  Mg interaction. The TSS/TA ratio ranged from 18.63 to 25.61. The highest was found at the 2.0 kg of Ca and 0.5 kg of Mg treatment. Two-way ANOVA revealed that TSS/TA was significantly affected by Mg and the Ca  $\times$  Mg interaction, with *p*-values of 0.005 and 0.001, respectively, although Ca alone had no significant effect. This indicates that the TSS/TA ratio, an indicator of the balance between fruit sweetness and acidity, is clearly influenced by Mg and the combination of Ca and Mg. Application of Mg improved key quality parameters of pummelo, with TSS/TA increasing by 19.51% (soil application) and 42.98% (foliar application) (Su et al., 2025). In general, the findings indicate that the mixture of 2.0 kg Ca and 0.5 kg Mg is the best to enhance TSS and the TSS/TA ratio.

### Correlation between yield, fruit quality, and soil chemical properties

The PCA analysis results (Figure 4) showed a relatively clear separation between the variable groups related to soil chemical properties, yield,

and fruit quality parameters. The PC1 axis mainly separated the variable group related to fruit cracking, TSS, yield, number of fruits, fruit circumference, and vitamin C from the variable group related to exchangeable Ca, exchangeable Mg, peel thickness, and TA. The fruit cracking rate and TSS were positioned on the positive side of PC1, indicating that these 2 indicators tended to vary in the same direction. Conversely, Ca, Mg, and peel thickness were on the negative side of PC1, showing an opposite trend to the fruit cracking rate and TSS. This suggests that increasing exchangeable Ca and Mg in the soil may reduce fruit cracking and change fruit peel characteristics. The PC2 axis is mainly related to pH, fruit juice yield, P, and Mg, while the opposite position between pH and TA reflects the contrasting relationship between pH and total acidity. Overall, the PCA results showed that variations in exchangeable Ca, Mg, and soil chemical properties were related to changes in fruit cracking rate, TSS, and several yield indicators.

Figure 5 shows the heatmap of Pearson correlation coefficients between yield, fruit quality, and soil chemical properties. There were no significant correlations between available soil P and yield or fruit quality parameters. Conversely, exchangeable K had significant positive relationships with major yield and quality characteristics, such as fruit weight ( $r = 0.82$ ), fruit circumference ( $r = 0.87$ ), yield ( $r = 0.79$ ), fruit cracking rate ( $r = 0.91$ ), TSS ( $r = 0.83$ ), and TSS/TA ( $r = 0.79$ ). There was a negative

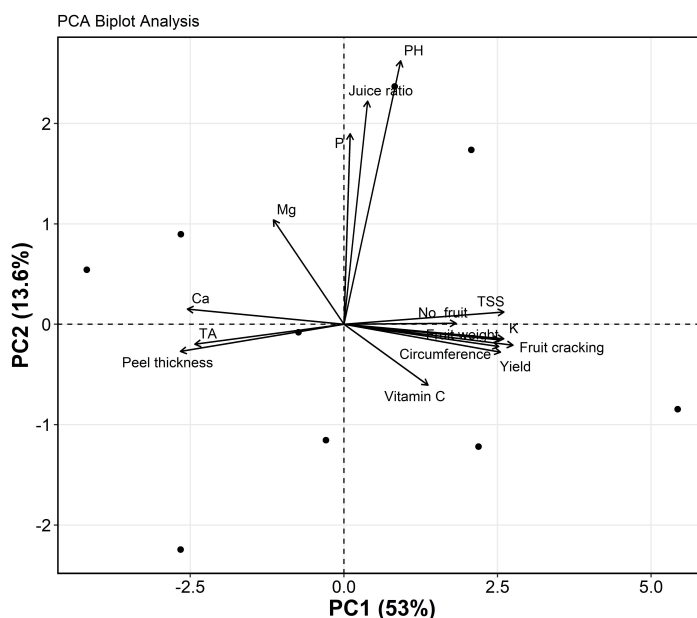


Figure 4. PCA correlation circle illustrating the relationships among soil and fruit quality indicators

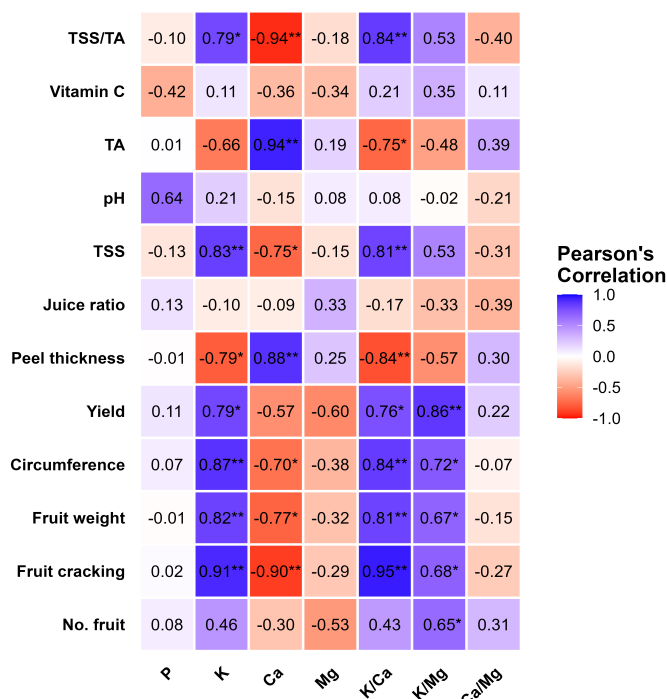


Figure 5. Heatmap of Pearson correlation coefficients between yield, fruit quality, and soil chemical properties

relationship between K and peel thickness ( $r = -0.79$ ). The K/Ca molar ratio was also positively correlated with fruit weight ( $r = 0.81$ ), circumference ( $r = 0.84$ ), yield ( $r = 0.76$ ), fruit cracking ( $r = 0.95$ ), and TSS/TA ( $r = 0.84$ ) and negatively correlated with peel thickness ( $r = -0.84$ ). The K/Mg molar ratio also demonstrated positive correlations with fruit number ( $r = 0.65$ ), fruit weight ( $r = 0.67$ ), circumference ( $r = 0.72$ ), yield ( $r = 0.86$ ), and fruit cracking ( $r = 0.68$ ). These trends underscore the pivotal role of K in the development and formation of fruits. This influence is likely due to the function of K in activating over 60 vital enzymes, which are very important in the formation of sugars and starches, the synthesis of proteins, and cell division. These mechanisms have a major impact on the yield and fruit quality parameters, especially TSS (Bustamante et al., 2021; Shah et al., 2024; Wu et al., 2024). Hien et al. (2026a) have also reported similar relationships and positive correlations between leaf K content and fruit circumference, fruit weight, juice volume, pH, and TSS in pummelo. Applying K at 225 kg ha<sup>-1</sup> significantly increased stevia biomass, K uptake, and TSS content (Fauzan et al., 2025).

There were no significant correlations between exchangeable Mg and the Ca/Mg molar ratio and yield or fruit quality characteristics. In contrast,

exchangeable Ca exhibited negative correlations with fruit weight ( $r = -0.77$ ), fruit circumference ( $r = -0.70$ ), fruit cracking ( $r = -0.90$ ), TSS ( $r = -0.75$ ), and TSS/TA ( $r = -0.94$ ). On the other hand, Ca had a positive relationship with fruit peel thickness ( $r = 0.88$ ). The relationships underscore the pivotal structural role of Ca in the formation of calcium pectate in the cell wall that facilitates cell division and ensures the structural integrity of cell membranes (Zhang et al., 2019; Jaime-Guerrero et al., 2024). Moreover, it has been found that increased Ca levels are linked to decreased TSS and sugar content in fruits (Dorostkar et al., 2022; Souza et al., 2023).

## CONCLUSIONS

The findings of this study demonstrate that Ca and Mg fertilization significantly enhances soil chemical properties, fruit yield, and quality parameters in Xa Doai oranges. Increased Ca application rates effectively raised soil pH and exchangeable Ca and Mg levels, although a concomitant reduction in exchangeable K. Crucially, the application of Ca and Mg markedly suppressed the incidence of fruit cracking, a result attributed to reinforcement of cell wall structural integrity. The combination of 2.0 kg Ca and 0.5 kg Mg produced the highest yield (50.84 kg tree<sup>-1</sup>), TSS (11.53 %), and TSS/TA (25.61). However, the results of this study were limited to

a single growing season and one specific orange cultivar. Further long-term studies are required to assess the long-term effects of these treatments on fruit cracking, fruit drop, yield, quality, and overall economic feasibility.

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