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Effects of Foliar Application of Micronutrients on Nutrient Uptake, Fruit Yield, and Quality of Xa Doai Oranges

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ABSTRACT

Xa Doai orange is a commercially valuable cultivar in Central Vietnam, yet its productivity and fruit quality are often limited by micronutrient deficiencies. This study aimed to evaluate the effects of foliar application of zinc sulfate ($ZnSO_4 \cdot 7H_2O$), manganese sulfate ($MnSO_4$), and boric acid (H_3BO_3) at varying concentrations (0%, 0.4%, 0.6%, 0.8%, and 1.0%) on nutrient uptake, fruit yield, and quality attributes of Xa Doai orange. The experiment was conducted over one growing season (2022–2023) in a randomised complete block design with five treatments and three replications. Foliar sprays were applied twice times during critical growth stages: fruit set, and fruit development. Each plot consisted of nine trees, and data were collected on leaf nutrient content, yield components, and juice quality parameters. The results showed that the 0.8% treatment (T4) significantly improved leaf nutrient concentrations (45.04 mg/kg Zn, 49.62 mg/kg Mn, 51.79 mg/kg B), fruit weight (221.79 g), and yield (39.55 kg/tree) compared to the control ($P \leq 0.05$). Juice content, total soluble solids (12.92 %), and vitamin C (468.00 mg/L) were also highest at this concentration. No significant changes in soil pH or residual micronutrients were observed. These findings indicate that foliar spraying of Zn, Mn, and B at 0.8% is an effective, environmentally safe strategy to enhance productivity and fruit quality in Xa Doai orange. Further studies are needed to assess long-term effects and economic viability under diverse agroecological conditions.

Keywords: Foliar application, micronutrients, nutrient uptake, Xa Doai oranges, yield, quality

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INTRODUCTION

Citrus fruits, especially oranges, are among the most economically significant fruit crops globally due to their nutritional value and consumer demand (Hussain et al., 2021; Liu et al., 2012). In Vietnam, the

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Xa Doai orange (*Citrus sinensis* L.) is a premium local cultivar well known for its distinctive aroma, juicy texture, and high sugar content. It plays a vital role in the agricultural economy of Nghe An Province, particularly in Quy Hop District, where it has traditionally accounted for a large share of total orange production. However, recent years have witnessed a marked decline in orange cultivation area—from 4,734.84 hectares in 2021 to just 1,849.33 hectares by August 2023 (Nghe An Department of Crop Production and Plant Protection [NADCPPP], 2023). This decline is largely attributed to reduced productivity, declining fruit quality, increased disease pressure, and poor soil fertility management.

One of the most pressing agronomic challenges is the widespread deficiency of essential micronutrients such as zinc (Zn), manganese (Mn), and boron (B) in orange orchards, particularly in regions with acidic soils and prolonged intensive farming systems such as those found in Nghe An. These deficiencies are becoming increasingly common due to soil leaching, excessive liming, and the limited application of micronutrient fertilisers (Alva & Tucker, 1999; Srivastava et al., 2015; Hiền et al., 2019). Although required in small quantities, these micronutrients are essential for enzymatic activation, cell division, sugar metabolism, photosynthesis, and hormone regulation (Hänsch & Mendel, 2009; Sahu et al., 2020; Mukherjee & Bordolui, 2022). Micronutrient deficiencies can lead to disrupted nutrient balance, resulting in reduced fruit set, poor fruit quality, and lower vitamin C content (Walli et al., 2022; Khatun et al., 2024).

Foliar application of micronutrients has emerged as an effective strategy to correct deficiencies and improve nutrient use efficiency, especially in perennial fruit trees like citrus. Several studies have demonstrated the beneficial effects of foliar micronutrient sprays on citrus and other fruit crops. For example, Ashraf et al. (2013) and Razzaq et al. (2013) reported increased yield and juice quality in citrus following foliar application of zinc. Similarly, foliar application of Mn and B improved photosynthesis, fruit quality, and vitamin C levels in Kinnow and sweet orange (Ilyas et al., 2015; Walli et al., 2022). Despite these findings, few studies have examined the optimal combinations and concentrations of micronutrients in Xa Doai oranges, especially under the ecological conditions of North Central Vietnam. Most farmers still rely on traditional knowledge or general fertiliser recommendations without scientific validation, leading to suboptimal results and inefficient resource use.

Given this context, the present study was undertaken with the following objectives:

1. To evaluate the effects of foliar application of Zn, Mn, and B at varying concentrations on the nutrient uptake efficiency of Xa Doai orange leaves;
2. To assess their impacts on fruit yield and quality attributes such as juice content, total soluble solids (TSS), titratable acidity (TA), and vitamin C content; and
3. To determine the optimal foliar micronutrient concentration that enhances both productivity and fruit quality under the agro-climatic conditions of Quy Hop District, Nghe An Province.

This research is geographically focussed on the tropical monsoon climate of North Central Vietnam and targets Xa Doai orange, a cultivar of high local and commercial importance with limited scientific data available. The findings are expected to provide agronomically relevant recommendations for micronutrient management in citrus farming systems, support sustainable production practices, and contribute to the scientific understanding of foliar nutrition strategies for fruit crops. Furthermore, this study may serve as a foundation for future research on nutrient interactions, economic returns of micronutrient use, and long-term effects on soil health and fruit quality.

MATERIALS AND METHODS

Experimental Site and Plant Material

The experiment was conducted from December 2022 to December 2023 at a commercial Xa Doai orange orchard in Quy Hop district, Nghe An province, Vietnam (19°19′N, 105°11′E). The site is located in a tropical monsoon climate zone, with annual rainfall of approximately 1,800 mm, average temperatures ranging from 15°C to 36°C, and relative humidity between 70–90%.

The soil at the study site was classified as loamy (45% sand, 30% silt, and 25% clay) with slightly acidic pH (6.03–6.43), moderate organic matter (2.1–2.5%), and low levels of available micronutrients (Zn, Mn, B). The orchard consisted of five-year-old Xa Doai orange trees grafted onto sour orange rootstock. Trees were planted at 4.0 m × 5.0 m spacing, with consistent orchard management practices applied throughout the study, including drip irrigation, pruning, weed control, and pest management.

Experimental Design and Treatments

The experiment was laid out in a randomised complete block design (RCBD) with five treatments and three replications. Each experimental plot had an area of 180 m^2 (12 m × 15 m), and nine trees were planted per plot, totalling 135 trees for the entire experiment. Details of the treatment combinations are presented in Table 1.

Table 1
Micronutrient concentrations in foliar spray treatments

Treatment	Foliar spray concentration (%)
T_1 (control)	Water only
T_2	0.4% $ZnSO_4.7H_2O$, $MnSO_4$, H_3BO_3
T_3	0.6% $ZnSO_4.7H_2O$, $MnSO_4$, H_3BO_3
T_4	0.8% $ZnSO_4.7H_2O$, $MnSO_4$, H_3BO_3
T_5	1.0% $ZnSO_4.7H_2O$, $MnSO_4$, H_3BO_3

The micronutrient solution was a mixture of $ZnSO_4$, $MnSO_4$, and H_3BO_3, diluted to the appropriate concentrations. Treatment concentrations were chosen based on prior studies and field trials in citrus nutrition (Hiền et al., 2019).

Treatments were randomly assigned within blocks. The same trees were used throughout the study for all measurements.

All treatments were applied in addition to the base fertiliser regimen commonly used by local farmers, which included 1.5–2 kg of lime, 40–60 kg of cow manure, 200–250 g N, 150–200 g P_2O_5, and 100–120 g K_2O per tree annually.

Foliar Application Procedures

Micronutrient solutions were freshly prepared before each application using distilled water. A 15-litre knapsack sprayer with a cone-type nozzle was used for foliar spraying. Each tree received approximately 2 litres of solution per spray.

Spraying was performed at twice key growth stages: fruit set (early May), and fruit development (mid-August). Sprays were applied early in the morning (6:30–8:00 AM) under favourable environmental conditions (ambient temperature 24–28°C, RH ~70%, wind speed <5 km/h) to maximise foliar absorption and reduce drift.

Soil Sampling and Analysis

Soil samples were collected twice: before treatment application (December 2022) and after treatment application (December 2023). Four soil cores were taken from the topsoil (0–20 cm) beneath the tree canopy using a soil auger, and composited into one sample per plot (15 composited samples per sampling time). Samples were air-dried, sieved through a 2-mm mesh, and stored in sealed plastic bags. Soil pH was determined in a 1:2.5 soil-to-water suspension using a pH metre.

Micronutrients (Zn, Mn, B, Fe) were extracted using DTPA (Lindsay & Norvell, 1978) and measured using atomic absorption spectrophotometry (AAS) (Jones, 2001; 2002).

Leaf Sampling and Analysis

Leaf samples were collected twice: in December 2022 (before treatment) and December 2023 (after treatment). From each tree, 20 fully expanded, aged 3 to 5 months, non-fruiting leaves were sampled from the fourth node of current-season shoots, with sampling done from all four canopy directions.

Leaves were washed with deionised water, oven-dried at 65°C to constant weight, ground into fine powder, and digested using a 2:1 mixture of HNO_3:$HClO_4$. The digested samples were filtered, diluted, and analysed for Zn, Mn, and B concentrations by AAS (Soil and Plant Analysis Council [APAC], 2000).

Data Collection and Analysis

Fruit samples were collected in December 2023 at the commercial maturity stage. The following parameters were evaluated using standard procedures:

1. Number of fruits per tree : All marketable fruits from each tree were counted manually at harvest and recorded as the total fruit number per tree.
2. Average fruit weight (g) : After counting, 30 harvested fruits from each tree were weighed using a digital balance (±0.01 g accuracy). The average fruit weight was calculated as the total fruit weight divided by the number of fruits.
3. Fruit diametre (cm) : The transverse diametre of each sampled fruit was measured at its widest point (equatorial region) using a digital Vernier caliper (±0.01 cm precision). Three fruits per tree were measured, and the average was used.
4. Peel thickness (cm) : Peel thickness was measured at three equidistant points around the equator of each fruit using the same caliper. The average of the three readings per fruit was used for analysis.
5. Total fruit yield per tree (kg) : The total fresh weight of fruits harvested per tree was recorded using a portable digital balance and expressed in kilogrammes.
6. Juice content (% by weight) : Each sampled fruit was manually juiced using a stainless-steel juicer. The juice was filtered and weighed. Juice content was calculated using the formula:

$$\text{Juice content (\%)} = \frac{\text{Juice weight}}{\text{Fruit weight}} \times 100$$

7. Total soluble solids (TSS) : A few drops of the freshly extracted juice were placed on the prism of a digital refractometer (ATAGO PAL-1, Japan), and the reading was recorded at 20°C.
8. Titratable acidity (TA, % citric acid) : Ten millilitres of filtered juice were diluted with 50 mL of distilled water and titrated against 0.1 N NaOH using phenolphthalein as an indicator (Boland, 1995). The endpoint was determined by the appearance of a persistent pink colour. Titratable acidity was calculated and expressed as % citric acid using the formula:

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

where 0.064 is the milliequivalent weight of citric acid.

9. Vitamin C content (mg/100 mL) : Vitamin C was determined using the 2,6-dichlorophenolindophenol (DCPIP) dye titration method. Ten millilitres of juice were titrated with standard DCPIP solution until a persistent pink endpoint was observed. The vitamin C content was calculated based on a standard ascorbic acid curve and expressed in mg/100 mL of juice.

All data were analysed using SPSS version 26.0. One-way analysis of variance (ANOVA) was conducted to evaluate treatment effects, and mean differences were separated using the Least Significant Difference (LSD) test at a 5% significance level ($P \leq 0.05$).

RESULTS AND DISCUSSION

Effect on Yield Components

The yield components of Xa Doai orange responded positively to foliar application of micronutrients, particularly at higher concentrations (Table 2). Among these components, the number of fruits per tree ranged from 177.44 to 180.44, showing no statistically significant differences among treatments ($P > 0.05$). This indicates that foliar micronutrient application had a limited effect on fruit set in this specific context. Similar results were reported by Hasani et al. (2012), who found that foliar Zn and Mn applications did not significantly affect fruit number in pomegranate. However, other studies have documented different outcomes. Singh et al. (2018) observed a significant increase in fruit count in sweet orange when treated with a foliar combination of 0.5% Zn, 0.7% B, and 0.7% Cu. Likewise, Bhanukar et al. (2021) and El-Gioushy et al. (2021) reported improved fruit number and overall productivity in citrus under specific micronutrient combinations.

Table 2
Effects of foliar application of micronutrients on the yield components and yield of the Xa Doai oranges

Treatment	Number of fruits/tree	Fruit weight (g/fruit)	Fruit diameter (cm)	Peel thickness (cm)	Yield (kg/tree)
T1	178.78^a	192.23^b	7.18^a	0.37^a	34.35^c
T2	176.89^a	199.70^b	7.40^a	0.36^a	35.33^b
T3	180.44^a	209.03^b	7.49^a	0.35^a	37.69^a
T4	178.22^a	221.79^a	7.52^a	0.32^a	39.55^a
T5	177.44^a	221.56^a	7.50^a	0.32^a	39.25^a
$LSD_{0.05}$	6.80	10.62	0.87	0,24	2.16
CV%	4.00	7.70	1.80	9.90	6.10

Note. Different letters within the columns indicate significant differences at $P \leq 0.05$

These contrasting findings underscore that the impact of foliar micronutrient application on fruit number is context-dependent, likely influenced by species, cultivar, baseline soil fertility, and environmental conditions.

In contrast to fruit number, fruit weight showed significant and consistent improvement with increasing foliar concentrations. Treatment T4 (0.8%) produced the heaviest fruits at 221.79 g, followed closely by T5 (1.0%) at 221.56 g. These values represent an increase of approximately 17.6% over the control (188.59 g), and the difference was statistically significant ($P \leq 0.05$). This enhancement is biologically meaningful, as heavier fruits directly contribute to higher market value and total yield. The low coefficient of variation (CV < 10%) and confirmed LSD values indicate high consistency and reliability of the treatment effects. These findings are in agreement with Bhanukar et al. (2021), who reported increased fruit weight in Blood Red oranges with 1.0% $ZnSO_4$ application, and Bhalerao et al. (2020), who found that $ZnSO_4$ + $MnSO_4$ foliar application improved fruit mass in sweet oranges.

Although fruit diameter also increased slightly from 7.18 cm in the control (T1) to 7.52 cm in the 0.8% treatment (T4), the differences were not statistically significant. However, this positive trend may be biologically meaningful and can be attributed to the physiological roles of zinc and boron in fruit development. Zinc activates key enzymes involved in protein and carbohydrate metabolism, facilitating better assimilate translocation to the fruit, while boron enhances sugar transport and cell wall expansion, contributing to increased fruit volume. Such micronutrient-driven processes improve cell division and elongation in the fruit's pericarp, potentially leading to larger diameters over time. Similar trends have been reported in other citrus studies, where foliar application of Zn and B, either individually or in combination, resulted in increased fruit diameter in sweet orange, mandarin, and related cultivars (Kamei et al., 2019; Makhoul et al., 2019; Mann et al., 1985; Zoremtluangi et al., 2019).

Peel thickness decreased gradually with higher foliar concentrations, from 0.37 cm in the control to 0.32 cm in T4 and T5. Although the difference was not statistically significant, thinner peel is a favourable trait for juice yield and consumer acceptance. This trend is supported by findings of Singh et al. (2018) and Luxmi et al. (2024), where reduced peel thickness was recorded in citrus under micronutrient spraying.

The most substantial improvement was recorded in total fruit yield per tree, where T4 (0.8%) achieved a mean yield of 51.79 kg/tree—an increase of 50.8% compared to the control (34.35 kg/tree). This difference was statistically significant ($P \leq 0.05$) and is of practical importance to commercial growers. The increase in yield is attributed to a combination of higher fruit weight and juice content, possibly resulting from improved nutrient availability and enhanced physiological processes such as photosynthesis and sugar translocation. Similar improvements were reported by Nandita et al. (2022), who found that combined foliar application of Zn, B, Cu, and Fe significantly improved sweet orange yield.

In summary, while fruit count per tree remained unchanged, foliar application of Zn, Mn, and B—particularly at 0.8%—enhanced fruit weight, yield, and peel traits, demonstrating its agronomic effectiveness for improving Xa Doai orange productivity under the conditions of Nghe An Province.

Impact on Fruit Quality

Fruit quality is a critical determinant of consumer preference and market value. In this study, foliar application of micronutrients (Zn, Mn, B) at increasing concentrations positively affected key quality attributes of Xa Doai oranges, including juice content, total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio, and vitamin C content (Table 3).

The juice content ranged from 41.34% in the control (T1) to a maximum of 51.55% in T4 (0.8%), representing a 24.7% increase. This improvement was statistically significant ($P \leq 0.05$) and is particularly important for juice yield and consumer satisfaction. These findings are supported by Razzaq et al. (2013) and Singh et al. (2018), who observed similar increases in juice content in citrus fruits following foliar Zn and B application.

TSS, an indicator of sugar concentration and sweetness, also improved significantly with increasing foliar concentrations. TSS increased from 10.3 in T1 to 12.92 % in T4—a 25.4% enhancement—indicating better carbohydrate accumulation and flavour development. This difference was statistically significant ($P \leq 0.05$) and aligns with the findings of Bhalerao et al. (2020), Hasani et al. (2012), and Walli et al. (2022), who demonstrated that foliar application of Zn and Mn enhances TSS in citrus and other fruit crops by improving photosynthetic efficiency and sugar translocation.

Table 3
Effects of foliar application of micronutrients on the quality attributes of Xa Doai oranges

Treatment	Juice content (%)	TSS (%)	TA (%)	TSS/TA	Vitamin C (mg/L)
T1	48.35^{c}	10.30^{e}	0.45^{a}	22.72^{d}	426.33^{c}
T2	48.57^{c}	11.16^{d}	0.39^{a}	28.94^{c}	432.11^{bc}
T3	53.04^{ab}	11.57^{c}	0.39^{a}	29.89^{c}	445.56^{b}
T4	53.82^{a}	12.92^{a}	0.36^{a}	36.36^{a}	468.00^{a}
T5	50.39^{bc}	12.37^{b}	0.38^{a}	32.98^{b}	445.78^{b}
$LSD_{0.05}$	3.01	0.44	0.13	1.46	17.50
CV%	8.80	5.70	4.80	7.30	6.00

Note. Different letters within the columns indicate significant differences at $P \leq 0.05$

Although titratable acidity (TA) did not differ significantly among treatments (range: 0.31–0.36%), the TSS/TA ratio, which serves as a flavour balance index, was highest in T4 (36.36), compared to 28.03 in the control. A higher TSS/TA ratio reflects better sweetness-acidity balance, a key determinant of fruit palatability and marketability. Singh et al. (2018) and Zoremtluangi et al. (2019) reported similar improvements in citrus taste profile with foliar micronutrient combinations.

Vitamin C content, a vital nutritional quality trait and antioxidant marker, also increased significantly under foliar treatment. The control recorded 426.33 mg/L, while T4 reached 468.00 mg/L—an enhancement of 9.8%. This aligns with studies by Ali et al. (2014) and Ilyas et al. (2015), which found that zinc and manganese foliar sprays enhance ascorbic acid synthesis due to their roles in enzymatic co-factors and oxidative metabolism.

Together, these results confirm that foliar application of Zn, Mn, and B at 0.8% concentration optimizes fruit quality in Xa Doai oranges. The improvements are not only statistically significant ($P \leq 0.05$) but also biologically and commercially meaningful, particularly for high-value speciality citrus such as Xa Doai, where flavour, juice yield, and nutritional value are key competitive advantages.

Soil and Plant Nutrient Status

Soil Properties

Soil analysis conducted before treatment application (December 2022) and after treatment application (December 2023) revealed no statistically significant differences in key parameters, including pH and DTPA-extractable Zn, Mn, B, and Fe concentrations (Table 4). The soil pH remained stable around 6.03–6.43, while available micronutrient levels showed only slight, non-significant variation across treatments. These results suggest that foliar application of micronutrients did not contribute to nutrient accumulation or chemical changes in the soil, which is consistent with the mode of application where nutrients are absorbed directly through leaf surfaces. Similar findings were reported by Bhalerao et al. (2020) and El-Gioushy et al. (2021), who also observed minimal impact of foliar micronutrient application on soil properties in citrus orchards.

From an environmental perspective, foliar fertilisation presents a lower risk of soil contamination and nutrient runoff, especially under intensive citrus management on sloping or sandy soils. However, repeated foliar application over multiple seasons could lead to localized accumulation in the phyllosphere or shallow soil layers due to leaf wash-off during rain events. Therefore, we recommend periodic soil testing and nutrient budgeting to prevent potential overuse and ensure long-term sustainability.

Table 4
Chemical properties of top-soils (0 to 20 cm) before and after treatment

Treatment	pH		Zn (mg/kg)		Mn (mg/kg)		B (mg/kg)		Fe (mg/kg)	
	Before	After	Before	After	Before	After	Before	After	Before	After
T_1	6.14[a]	6.25[a]	2.01[a]	1.91[a]	9.40[a]	10.93[a]	0.38[a]	0.36[a]	31.17[a]	34.07[a]
T_2	6.30[a]	6.19[a]	2.00[a]	1.95[a]	9.73[a]	9.13[a]	0.39[a]	0.37[a]	36.63[a]	39.17[a]
T_3	6.03[a]	6.34[a]	2.03[a]	1.98[a]	10.93[a]	11.97[a]	0.37[a]	0.36[a]	34.07[a]	36.17[a]
T_4	6.26[a]	6.43[a]	2.31[a]	2.16[a]	8.13[a]	10.43[a]	0.40[a]	0.38[a]	39.17[a]	36.63[a]
T_5	6.21[a]	6.20[a]	2.14[a]	2.08[a]	8.97[a]	9.00[a]	0.39[a]	0.38[a]	35.33[a]	34.02[a]
$LSD_{0.05}$	0.30	0.46	0.49	0.26	3.96	4.39	0.12	0.20	8.16	5.88
CV%	2.60	3.90	12.30	6.70	9.10	14.70	3.20	3.50	12.20	11.50

Note. Different letters within columns indicate significant differences at $P \leq 0.05$

Table 5
Effects of foliar application of micronutrients on leaf nutrient content of the orange tree

Treatment	Zn (mg/kg)		Mn (mg/kg)		B (mg/kg)		Fe (mg/kg)	
	Before	After	Before	After	Before	After	Before	After
T_1	21.15[a]	19.25[c]	21.68[a]	22.96[d]	30.24[a]	31.61[e]	65.62[a]	60.19[c]
T_2	20.92[a]	41.82[b]	22.68[a]	44.43[c]	31.12[a]	46.69[d]	66.05[a]	68.93[b]
T_3	22.68[a]	42.46[b]	21.82[a]	47.15[b]	30.81[a]	48.31[c]	67.56[a]	73.63[a]
T_4	21.91[a]	45.04[a]	21.57[a]	49.62[a]	31.43[a]	51.79[a]	64.22[a]	75.04[a]
T_5	20.27[a]	43.30[b]	20.77[a]	46.46[b]	29.62[a]	50.67[a]	69.53[a]	76.38[a]
$LSD_{0.05}$	3.63	1.69	2.23	1.75	3.49	1.66	4.46	3.98
CV%	9.00	2.30	5.50	2.20	6.10	1.09	3.60	3.20

Note. Different letters within the columns indicate significant differences at $P \leq 0.05$

Leaf Nutrient Uptake

Significant differences were observed in leaf nutrient concentrations among treatments (Table 5). The highest leaf Zn, Mn, and B concentrations were recorded in T4 (0.8%): 45.04 mg/kg for Zn, 49.62 mg/kg for Mn, 51.79 mg/kg for B, and 75.04 mg/kg for Fe—substantially higher than in the control (T1), and above the sufficiency thresholds for citrus as reported by Alva and Tucker (1999).

The elevated concentrations of Zn, Mn, B, and Fe in leaf tissues were closely associated with notable improvements in yield and fruit quality attributes—particularly higher fruit weight, juice content, total soluble solids (TSS), and vitamin C levels (Walli et al., 2022). Similar correlations between foliar micronutrient uptake and enhanced productivity in citrus and other fruit crops have also been documented in previous studies (Bhalerao et al., 2020;

El-Gioushy et al., 2021; Hasani et al., 2012), further supporting the positive relationship between nutrient absorption efficiency and agronomic performance.

This enhanced nutrient uptake efficiency may be attributed to favourable conditions during foliar application, such as increased leaf permeability and stomatal conductance in the early morning under moderate relative humidity (Maity et al., 2021). Bhalerao et al. (2020) also emphasised that timing and environmental conditions during spray application are critical for maximising absorption and utilisation efficiency. Moreover, the physiological functions of these micronutrients play a crucial role in supporting plant metabolism and reproductive success. Zinc promotes auxin biosynthesis and activates numerous enzymes involved in protein metabolism (Nayan & Fouzi, 2023; Kumar et al., 2024); manganese is essential for chloroplast development, the water-splitting reaction of photosystem II, and the regulation of oxidative stress (Uthman et al., 2022); while boron facilitates sugar transport, stabilises cell walls, and plays a pivotal role in pollen germination and fruit set (Razzaq et al., 2013; Singh et al., 2018; Walli et al., 2022).

These mechanisms together contributed to enhanced photosynthesis, assimilate partitioning, and reproductive development, ultimately resulting in greater fruit biomass and better internal quality. Comparable physiological responses to foliar micronutrient treatments have been documented by Zoremtluangi et al. (2019), who reported improved leaf nutrient content and fruit characteristics in Khasi mandarin under combined Zn–Mn–B foliar application.

CONCLUSION

This study confirmed that foliar application of micronutrients—zinc (Zn), manganese (Mn), and boron (B)—significantly improved nutrient uptake, yield components, and fruit quality of Xa Doai orange under the agroecological conditions of Nghe An Province, Vietnam. Among the tested treatments, the 0.8% foliar concentration (T4) was the most effective. The application of $ZnSO_4$, $MnSO_4$, and H_3BO_3 at 0.8% increased fruit weight by 17.6% and total yield by 50.8% compared to the control. While the number of fruits per tree remained statistically unchanged, significant improvements were recorded in juice content (+24.7%), total soluble solids (TSS, +25.4%), and vitamin C content (+9.8%). These quality attributes are crucial for consumer preference and processing value. Elevated leaf concentrations of Zn, Mn, and B confirmed improved uptake efficiency without causing accumulation in soil or altering soil pH, highlighting the environmental safety of foliar application. These findings suggest that spraying at 0.8% during key stages— fruit set, and fruit development—can be a practical strategy to boost both yield and quality in Xa Doai orange cultivation.

However, this study was conducted over a single growing season and limited to one cultivar. Further research should assess the long-term effects, economic returns, and optimisation of application frequency and timing under varied conditions. Overall, the results indicate that foliar micronutrient application is a promising and sustainable approach to improving orange production in central Vietnam.

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