profiles of citrus orchard nutrition and fruit quality in Hunan Province, China

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**ABSTRACT**

Understanding of orchard nutrition status can facilitate the proper management of orchards for higher fruit yield and quality. From 2011 to 2019, the nutrition status of orchards in Hunan Province, a major citrus-producing area in china, were assessed. A total of 361 soil samples, 378 leaf samples and 285 fruit samples of sweet oranges including navel orange (\textit{citrus sinensis} l. Osbeck ‘newhall’) and common sweet orange (\textit{citrus sinensis} l. Osbeck ‘bingtangcheng’), and mandarins including satsuma mandarin (\textit{citrus unshiu} marc. ‘miyagawa’) and ponkan (\textit{citrus reticulata} blanco ‘xinnu’) were collected. These samples were from112 sweet orange orchards and 140 mandarin orchards. Parameters of soil, leaf and fruit nutrition and fruit quality were analyzed based on these samples. The results revealed that soil acidification occurred in 79.0% of sweet orange orchards (ph 3.56 to 8.12) and 74.7% of mandarin orchards (ph 2.75 to 8.15). Soil organic matter (om) was abundant in both sweet orange orchards (21.3 g/kg on average) and mandarin orchards (19.77 g/kg on average). Nutrient analysis demonstrated deficiencies of nitrogen (n), potassium (k) and boron (b) in soils and leaves of sweet orange and mandarin orchards. Zinc (zn) was abundant in soils but deficient in leaves, suggesting a low zn utilization efficiency in these orchards. Besides, excessive iron (fe), magnesium (mn) and copper (cu) were found in sweet orange and mandarin leaves, which may be associated with low soil ph and fungicides application in this area. The average contents of n, phosphorus (p) and k in the fruit were about 0.80%, 0.11% and 0.51%, respectively, with a ratio close to 1:0.14:0.6. Multiple linear regression (mlr) analysis revealed that leaf npk and molybdenum (mo) significantly affect fruit fresh fruit weight (ffw) and total soluble solids (tss), and leaf p is closely correlated with fruit titratable acid (ta).

**KEYWORDS**

Sweet orange; mandarin; orchard nutrition; fruit quality; nutrient analysis

**Introduction**

Citrus is one of the important fruit crops with an annual yield of over 140 million tons worldwide (FAO, 2019). Hunan Province is a conventional citrus-producing area in China, where sweet oranges and mandarins are mainly planted. In 2019, Hunan Province had approximately 400 hectares (ha) in citrus planting area and 5.6 million tons in fruit yield. In the whole industry, sweet oranges and mandarins account for 27.8% and 58.5% in planting area and 31.5% and 53.6% in annual yield, respectively (Deng et al., 2018). Citrus orchards in Hunan Province are usually located on hill lands and generally held by local smallholders, and as a consequence, fertilizer management is rather poor. With the increasing costs of labor and production goods in past decades, many smallholders cut down their investment in orchard management. Poor soil condition of hill citrus orchard coupling with low
doses and imbalance of fertilizers all make problems of citrus production in Hunan producing area (Ma et al., 2018). Imbalanced plant nutrition, the decline of soil fertility and fruit quality are common problems in most Hunan citrus orchards. Previous research studies have established the diagnosis criteria for soil and leaf nutrition in citrus orchards (Lu et al., 2002; Menino, 2012; Tang et al., 2013; Tao et al., 2016), and that supplied us with a guideline for orchard management. Therefore, a nutrient analysis for soils and plants in Hunan citrus orchards is highly necessary for reasonable orchard management and promoting sustainable production (Guo et al., 2019; Pestana et al., 2005).

As an evergreen and perennial plant, citrus has a high demand for nutrients, and essential mineral elements are critical for its fruit quality and yield. Citrus has high requirements for macro-nutrients like nitrogen (N), phosphorous (P) and potassium (K), and deficiency or excess of these nutrients can be detrimental to fruit quality and yield (Kadyampakeni et al., 2015; Wang et al. 2015). A low N content in soil may cause a gradual decline in fruit production by reducing the leaves and tree growth (Mattos et al., 2020). P deficiency may lead to a lower citrus yield, and an increase in soil P can reduce fruit acid concentration and increase the total soluble solids (TSS)/titratable acidity (TA) ratio (Zekri et al., 2015). The response of fruit quality to K availability is associated with the contents of glucose, fructose and soluble sugars in the fruit (Pettigrew, 2010; Schwarz et al., 2013). Manganese (Mn), iron (Fe), zinc (Zn), copper (Cu), boron (B) and molybdenum (Mo) are the main micro-nutrients required by fruit crops. The availability of adequate micro-nutrients can greatly improve fruit yield, quality and tree growth (Vashisth and Kadyampakeni, 2020). For example, foliar application of Zn improves citrus fruit quality including the TSS/TA and soluble sugars (Razzaq et al., 2013). Soil fertility parameters, including soil pH, organic matter (OM) and mineral nutrients affect soil structure, biological functions, aeration, water retention and nutrient absorption by plant roots (Diacono and Montemurro, 2011). Soil fertility and leaf nutrients are important indicators of plant nutrition status, which greatly impact citrus plant growth, fruit yield and quality.

In 2020, the citrus production of Hunan Province ranked amongst the top three in China, but little is known about the overall nutrient profile in the citrus orchards. Therefore, it is highly necessary to reveal the soil fertility, plant nutrients and fruit quality of Hunan producing area, which will further help to improve fruit yield and nutrient management of citrus. In the present work, soil, leaf and fruit samples were collected from the orchards of sweet oranges including Navel orange (Citrus sinensis L. Osbeck ‘Newhall’) and common sweet orange (Citrus sinensis L. Osbeck ‘Bingtangcheng’) and mandarins including Satsuma mandarin (Citrus unshiu Marc. ‘Miyagawa’) and Ponkan (Citrus reticulata Blanco ‘Xinnu’) in Hunan Province from 2011 to 2019. Through analysis of related parameters based on these samples, this study aims to reveal the relationships among soil nutrition, leaf nutrition and fruit quality. The findings are expected to improve the understanding of citrus orchard nutrition in Hunan Province, and provide important implications for future orchard management.

Materials and methods

Sample collection

Orchards in this study were involved in 34 counties (252 orchards in total) across Hunan Province, China (25°04’~29°32’N, 106°20’~112°64’E) (Figure 1). The annual average temperature was 16°C to 19°C and the annual average precipitation was 1400 mm to 1600 mm in this area (Figure 2) The samples comprised of sweet oranges including ‘Newhall’ navel orange (Citrus sinensis (L.) Osbeck.) and in part other sweet oranges like ‘Bingtangcheng’ (Citrus sinensis (L.) Osbeck.) and mandarins including Satsuma mandarin (Citrus unshiu Marc. ‘Miyagawa’) and Ponkan (Citrus reticulata Blanco’Xinnu’). All plants were grafted on trifoliolate orange (Poncirus trifoliata (L.) Raf.) with average plant age about 15 years.

Overall, a total of 361 soil samples, 378 leaf samples and 285 fruit samples were obtained from 121 sweet orange orchards and 140 mandarin orchards, with 35 to 45 soil, leaf and fruit samples collected
annually from 2011 to 2019. Soil samples were collected from 20 to 30 cm depth and each soil sample was a mixture of 15 to 20 random sub-samples per orchard (Guo et al., 2019). After air drying, the soil samples were gently ground, sieved (2 mm) and properly stored for further analysis. Leaf samples were collected from the top second or third node of a vegetative spring shoot, and each leaf sample comprised of 50 to 100 leaves with 10 leaves collected from each of 5 to 10 plants per orchard (Li et al., 2015). Along with leaf sampling, fruits were sampled from the same plants and each sample consisted of at least 10 fruits. Matched soil, leaf and fruit samples were collected from different plants.
between years, and the plants were selected in a specific orchard area. All samples (soil, leaf and fruit) were collected at harvest season in late November to early December for sweet orange, middle October for Satsuma mandarin and late November for Ponkan.

**Soil Nutrient Analysis**

Soil pH was determined in 1:2.5 (soil: water) soil water suspensions by using a pH-meter. The soil OM was determined with the potassium dichromate method (Bao, 2000). Alkaline N was determined with the alkaline hydrolysis diffusion absorption method (Li et al., 2015). Available P was extracted by the sodium bicarbonate and determined as described according to the Olsen method (Olsen and Sommers, 1982). Available K was extracted with ammonium acetate (Li et al., 2015), and available Fe, Mn, Cu and Zn were extracted with solutions of diethylene triamine pentaacetic acid (DTPA) (Bao, 2000). The extraction of water-soluble B was performed with boiled water, and that of available Mo was conducted with ammonium acetate (Bao, 2000). The measurements of available K, Fe, Mn, Cu, Zn, B and Mo above were carried out by inductively coupled plasma mass spectrometry (ICP-MS) (Qi et al., 2007).

**Analysis of Mineral Elements in Leaves and Fruits**

Leaf and fruit samples were washed with deionized water and inactivated by heating to 105°C for 15 min. The inactivated samples were dried at 65°C in a forced-air oven to constant weight, ground manually and stored for further analysis. Leaf samples were digested by using hydrogen peroxide and sulfuric acid for NPK determinations (Parkinson 1975). N in leaves and fruits was determined with the Kjeldahl method (Wen et al. 2015). P was extracted and determined spectrophotometrically as blue molybdate-phosphate complexes (Pestana et al., 2005), and K was measured with the flame photometry method. Available Fe, Mn, Cu, Zn, B and Mo in leaves were digested by dry ashing method (Enders and Lehmann, 2012) and determined by ICP-MS (Qi et al., 2007).

**Fruit Quality Analysis**

The fruit quality parameters of each sample (10 fruits per sample) was determined in terms of fresh fruit weight (FFW), total soluble solids (TSS) and titratable acidity (TA). Fresh fruit weight was measured by a digital electronic balance with 1% accuracy for the average weight of a single fruit. The TSS was measured as Brix° using the juice with a refractometer (PAL-BX, ATAGO). Fruit TA was determined by titration with an aliquot of juice against 0.1 M sodium hydroxide (Liu et al., 2014).

**Statistical Analysis**

The data in Tables 1, 2, 3 were presented as mean ± standard deviation (SD), and computed by using Microsoft Office Excel2007. Pearson correlations in Figure 4 were test at $P < .05$ or $P < .01$ by using SPSS18.0. Multiple regression analysis in Table 4 were performed by using SPSS18.0, the method for variance of analysis tested by F-test, $P < .05$. Figure 1 was outputted by ArcGIS software, Figures 2 and 3 were drawn by Graphpad prism 6.03, and Figure 4 was made by using the corrplot library in R version 3.2.2.

**Results**

**Overview of Soil pH, Organic Matter and Nutrients in Hunan Citrus Orchards**

In Hunan citrus orchards, the soils were generally characterized by low pH, abundant OM and imbalanced soil nutrients. Soil acidification occurred widely in Hunan citrus orchards, as indicated by the average soil
Table 1. Soil nutrients in sweet Orange and mandarin orchards of Hunan Province.

| Orchard type | Nutrients       | Sample size | Range   | Deficiency | Low | Optimum | High | Excess |
|--------------|----------------|-------------|---------|------------|-----|---------|------|--------|
|              |                |             | Min     | Max        | Mean ± SD | CV/% | samples | %    | samples | %    | samples | %    | samples | %    | samples | %    | samples | %    |
| Sweet orange| Alkaline N(mg/kg) | 133         | 20.0    | 257.0     | 82.8 ± 43.6 | 52.7 | 30      | 22.6 | 68      | 51.1 | 32      | 24.1 | 3      | 2.3  | \     | \     | \     | \     |
|              | Available P(mg/kg) | 133         | 0.0     | 99.5      | 15.2 ± 17.3 | 114.0 | 42      | 31.6 | 49      | 36.8 | 41      | 30.8 | 1      | 0.8  | \     | \     | \     | \     |
|              | Available K(mg/kg) | 133         | 7.9     | 363.5     | 108.8 ± 75.8 | 69.7 | 27      | 20.3 | 46      | 34.6 | 46      | 34.6 | 14     | 10.5 | \     | \     | \     | \     |
|              | Available Fe(mg/kg) | 133         | 0.5     | 251.9     | 51.2 ± 52.2 | 102.0 | 13      | 9.8  | 10      | 7.5  | 19      | 14.3 | 41     | 30.8 | 50     | 37.6 | \     | \     | \     | \     |
|              | Available Mn(mg/kg) | 133         | 0.1     | 129.5     | 20.9 ± 23 | 110.4 | 16      | 12.0 | 25      | 18.8 | 41      | 30.8 | 36     | 27.1 | 15     | 11.3 | \     | \     | \     | \     |
|              | Available Cu(mg/kg) | 133         | 0.1     | 4.1       | 0.9 ± 0.8 | 94.1  | 31      | 23.3 | 25      | 18.8 | 37      | 27.8 | 23     | 17.3 | 17     | 12.8 | \     | \     | \     | \     |
|              | Available Zn(mg/kg) | 133         | 0.1     | 2.6       | 0.3 ± 0.4 | 141.6 | 55      | 41.4 | 34      | 25.6 | 30      | 22.6 | 14     | 10.5 | 0      | 0    | \     | \     | \     | \     |
|              | Available B(mg/kg)  | 133         | 0.0     | 0.2       | 0.1 ± 0.1 | 62.7  \  | 35     | 26.3 | 90      | 67.7 | 8       | 6    | 0      | 0    | \     | \     | \     | \     |
| Mandarin    | Alkaline N(mg/kg)  | 228         | 19.52   | 203.06    | 823 ± 32.7 | 39.7 | 36      | 15.8 | 133     | 58.3 | 58      | 25.4 | 2      | 0.9  | \     | \     | \     | \     |
|              | Available P(mg/kg) | 228         | 0.48    | 733.9     | 479 ± 85 | 177.5 | 44      | 19.3 | 55      | 24.1 | 98      | 43.0 | 32     | 14.0 | \     | \     | \     | \     |
|              | Available K(mg/kg) | 228         | 8.19    | 551.33    | 1278 ± 80.1 | 62.7 | 35      | 15.4 | 59      | 25.9 | 97      | 42.5 | 37     | 16.2 | \     | \     | \     | \     |
|              | Available Fe(mg/kg) | 228         | 1.18    | 306.27    | 642 ± 60.5 | 94.1 | 45      | 6.6  | 14      | 6.1  | 18      | 7.9  | 80     | 35.1 | 102    | 44.7 | \     | \     | \     | \     |
|              | Available Mn(mg/kg) | 228         | 0.05    | 126.91    | 29 ± 24.1 | 83.0  | 10      | 4.4  | 20      | 8.8  | 69      | 30.3 | 93     | 40.8 | 37     | 16.2 | \     | \     | \     | \     |
|              | Available Cu(mg/kg) | 228         | 0.03    | 12.51     | 1.3 ± 1.7 | 136.0 | 36      | 15.8 | 39      | 17.1 | 63      | 27.6 | 53     | 23.2 | 38     | 16.7 | \     | \     | \     | \     |
|              | Available Zn(mg/kg) | 228         | 0.04    | 21.73     | 2.4 ± 2.8 | 116.9 | 40      | 17.5 | 34      | 14.9 | 131     | 57.5 | 19     | 8.3  | 5      | 2.2  | \     | \     | \     | \     |
|              | Available B(mg/kg)  | 228         | 0       | 1.19      | 0.2 ± 0.2 | 97.9  | 86      | 37.7 | 61      | 26.8 | 68      | 29.8 | 14     | 6.1  | 0      | 0    | \     | \     | \     | \     |
|              | Available Mo(mg/kg) | 228         | 0       | 0.75      | 0.1 ± 0.1 | 77.0  \  | 38     | 16.7 | 145     | 63.6 | 31      | 13.6 | 15     | 6.6  | \     | \     | \     | \     |
Table 2. Leaf nutrients in sweet Orange and mandarin in Hunan Province.

| Orchard type | Nutrients | Sample size | Range | CV/% | Sample size | Range | CV/% | Sample size | Range | CV/% | Sample size | Range | CV/% |
|--------------|-----------|-------------|-------|------|-------------|-------|------|-------------|-------|------|-------------|-------|------|
| Sweet orange leaf | N (%) | 122 | 1.4 - 3.3 | 2.1 ± 0.4 | 19.7 | 90 | 73.8 | 9 | 7.4 | 3 | 2.5 | 17 | 13.9 | 3 | 2.5 |
| | P (%) | 122 | 0.1 - 0.3 | 0.2 ± 0.1 | 34.5 | 15 | 12.3 | 16 | 13.1 | 33 | 27.0 | 57 | 46.7 | 1 | 0.8 |
| | K (%) | 122 | 0.3 - 1.6 | 0.8 ± 0.3 | 35.1 | 48 | 39.3 | 54 | 44.3 | 20 | 16.4 | 0 | 0 | 0 | 0 |
| | Fe(mg/kg) | 122 | 49.7 - 363.9 | 103 ± 48.4 | 47.0 | 7 | 0 | 1 | 0.8 | 99 | 81.1 | 19 | 15.6 | 3 | 2.5 |
| | Mn(mg/kg) | 122 | 1.5 - 65.6 | 22.7 ± 13.1 | 70.2 | 9 | 7.4 | 11 | 9.0 | 80 | 65.6 | 22 | 18.0 | 0 | 0 |
| | Cu(mg/kg) | 122 | 1.1 - 210.4 | 62.5 ± 43.9 | 57.6 | 14 | 11.5 | 5 | 4.1 | 9 | 7.4 | 15 | 12.3 | 79 | 64.8 |
| | Zn(mg/kg) | 122 | 0.3 - 1.6 | 0.8 ± 0.3 | 35.1 | 48 | 39.3 | 54 | 44.3 | 20 | 16.4 | 0 | 0 | 0 | 0 |
| | B(mg/kg) | 34 | 0.1 - 0.7 | 0.3 ± 0.1 | 39.6 | 0 | 0 | 1 | 2.9 | 33 | 97.1 | 0 | 0 | 0 | 0 |
| Mandarin leaf | N (%) | 256 | 1.1 - 3.7 | 2.1 ± 0.5 | 23.4 | 151 | 59.0 | 34 | 13.3 | 30 | 11.7 | 31 | 12.1 | 10 | 3.9 |
| | P (%) | 256 | 0.1 - 1.4 | 0.2 ± 0.1 | 73.4 | 13 | 5.1 | 47 | 18.4 | 137 | 53.5 | 58 | 22.7 | 1 | 0.4 |
| | K (%) | 256 | 0.2 - 1.9 | 0.7 ± 0.3 | 39.9 | 136 | 52.9 | 103 | 40.1 | 15 | 5.8 | 2 | 0.8 | 0 | 0 |
| | Fe(mg/kg) | 256 | 42.7 - 993.7 | 149.1 ± 89.1 | 59.7 | 0 | 0 | 5 | 1.9 | 124 | 48.2 | 106 | 41.2 | 21 | 8.2 |
| | Mn(mg/kg) | 256 | 12.3 - 423.2 | 83.7 ± 61.4 | 73.4 | 3 | 1.2 | 13 | 5.1 | 161 | 62.6 | 78 | 30.4 | 1 | 0.4 |
| | Cu(mg/kg) | 256 | 1.2 - 41.7 | 13.7 ± 11 | 79.9 | 49 | 19.1 | 32 | 12.5 | 62 | 24.1 | 19 | 7.4 | 94 | 36.6 |
| | Zn(mg/kg) | 256 | 0.6 - 88.6 | 17.7 ± 9.5 | 53.4 | 150 | 58.4 | 79 | 30.7 | 25 | 9.7 | 2 | 0.8 | 0 | 0 |
| | B(mg/kg) | 123 | 8.5 - 145.0 | 47.2 ± 27.8 | 58.9 | 21 | 16.9 | 30 | 24.2 | 67 | 54.0 | 5 | 4.0 | 0 | 0 |
| | Mo(mg/kg) | 123 | 0.1 - 0.7 | 0.2 ± 0.2 | 80.9 | 13 | 10.5 | 34 | 27.4 | 76 | 61.3 | 0 | 0 | 0 | 0 |
Table 3. Fruit NPK and quality characteristics in sweet Orange and mandarin.

| Citrus type | Fruit nutrients | Samples | Mean ± SD | Range | Min | Max | CV/% |
|-------------|-----------------|---------|-----------|-------|-----|-----|------|
| Sweet orange | N (%)           | 101     | 0.75 ± 0.17 | 0.4 | 1.35 | 22.8 |
|            | P (%)           | 101     | 0.12 ± 0.03 | 0.04 | 0.18 | 27.6 |
|            | K (%)           | 101     | 0.51 ± 0.16 | 0.22 | 0.94 | 32.0 |
|            | TSS (%)         | 72      | 181.09 ± 63.29 | 23.33 | 310 | 35.0 |
| Mandarin fruits | FFW (g)    | 72      | 0.64 ± 0.26 | 0.08 | 1.55 | 40.2 |
|            | TSS/TA          | 72      | 16.58 ± 9.24 | 6.3 | 42.59 | 55.7 |
|            | TA (g/100 ml)   | 145     | 118.98 ± 26.68 | 38.3 | 230 | 22.4 |
|            | FFW (g)         | 145     | 10.65 ± 1.12 | 7.6 | 13.57 | 10.5 |
|            | TA (g/100 ml)   | 145     | 0.98 ± 0.34 | 0.45 | 1.97 | 34.2 |
|            | TSS/TA          | 145     | 12.14 ± 4.47 | 4.3 | 27.4 | 36.8 |

pH of about 5.0 in sweet orange orchards and about 5.2 in mandarin orchards. Assuming an optimum pH range of 5.5 to 6.5 (Lu et al., 2002), soil acidification was observed in up to 79.0% of sweet orange orchards and 74.7% of mandarin orchards, while only 14.2% of sweet orange orchards and 15.1% of mandarin orchards exhibited the optimum soil pH (Figure 3 A and B). In addition, slight soil acidification (pH of 4.8 to 5.4) was found in 35.1% of mandarin orchards and 19.2% of sweet orange orchards. Soil OM was abundant in both sweet orange orchards (21.3 g/kg on average) and mandarin orchards (19.7 g/kg on average) (Figures 3 C and D). Assuming an optimum soil OM range of 10 to 15 g/kg (Lu et al., 2002), the result indicated that 13.6% of sweet orange orchards and 20.4% of mandarin orchards were optimum in OM, 74.8% of sweet orange orchard and 68.7% of mandarin orchard had high soil OM.

Most orchards were characterized by low soil alkaline N, appropriate Zn, but high available Fe and Mn (Table 1). Low soil alkaline N was found in 51.1% of sweet orange orchards and 58.3% of mandarin orchards. However, excessive soil available Fe was observed in 37.6% of sweet orange orchards and 44.7% of mandarin orchards. Differently, 63.9% of sweet orange and 57.5% of mandarin orchards showed appropriate levels of soil available Zn. The coefficients of variation (CV) for soil available P, Fe, Cu, Zn and B varied greatly above 90%. For instance, although the average values of available B, P and K were within the optimum range, over 40.0% of soil samples were deficient to low in available P and K, and the available B in over 60% of soil samples were lower than the optimum in both sweet orange and mandarin orchards (Table 1).

Leaf Nutrient Conditions in Hunan Citrus Orchards

Overall, 81.2%, 83.6%, 83.6% and 85.3% of sweet orange orchards were deficient to low for leaf N, K, Zn and B, respectively, and in mandarin orchards, the corresponding percentages were 72.3%, 94.0%, 89.1% and 41.1% (Table 2). By contrast, 46.7% of sweet orange orchards showed high P in citrus leaves; and the leaves in 64.8% of sweet orange orchards and 36.6% of mandarin orchards were of excessive Cu. Most orchards showed appropriate or high levels of Fe, Mn and Mo in leaves (Table 2).

Fruit NPK and Quality Characteristics of Sweet Oranges and Mandarins in Hunan Province

Sweet orange and mandarin fruits shared consistent nutrient profile. Both citrus types had high fruit N (about 0.80%), medium fruit K (about 0.51%) and low fruit P (about 0.11%) (Table 3). The N: P: K ratio in both citrus types was close to 1:0.14:0.6. The average FFW of sweet orange was 181.09 g and that of mandarin fruit was 118.98 g. Sweet orange fruit and mandarin fruit exhibited an average TSS of
11.3 Brix° and 10.65 Brix°, respectively. In terms of fruit flavor, sweet orange fruit showed a TSS/TA ratio of 16.58 and mandarin fruit had a TSS/TA ratio of 12.14 (Table 3).

Correlations between Soil, Leaf and Fruit Parameters

Correlation analysis revealed that just a few nutrients showed significant correlations between leaves and soils. Soil available Zn was positively correlated with leaf Zn and Cu in both sweet oranges and
mandarins. Soil available Mo had positive correlations with leaf N, P and K, but was negatively correlated with leaf Cu and Zn in both citrus orchards. For plant nutrients, leaf K exhibited positive correlations with fruit K in sweet oranges and mandarins. On the contrary, fruit N was negatively correlated with leaf P in both citrus types (Figure 4).

**Effects of Citrus Leaf and Fruit Nutrients on Fruit Quality**

Multiple linear regression (MLR) was employed to predict the effects of leaf and fruit nutrients on citrus fruit quality. In the analysis, nutrients in the leaf including leaf N ($X_{leaf\ N}$), leaf P ($X_{leaf\ P}$), leaf K ($X_{leaf\ K}$), leaf Fe ($X_{leaf\ Fe}$), leaf Mn ($X_{leaf\ Mn}$), leaf Cu ($X_{leaf\ Cu}$), leaf Zn ($X_{leaf\ Zn}$), leaf Mo ($X_{leaf\ Mo}$) and leaf B ($X_{leaf\ B}$) were treated as independent variables, while fruit quality parameters including FFW (Y$_{FFW}$), TSS (Y$_{TSS}$), TA (Y$_{TA}$) and TSS/TA ratio (Y$_{TSS/TA}$) were treated as dependent variables. Variance analysis of the equations showed that $P < .05$, suggesting that the β coefficients and variables of the equations could predict the positive and negative impacts of leaf nutrients on fruit quality and their contribution rate. The MLR analysis suggested that leaf NPK and Mo contributed significantly to the FFW and TSS/TA of fruit. Besides, leaf P contributed greatly to TSS with a β coefficient of 13.3 (Table 4).

**Discussion**

**Soil Nutrient Conditions of Citrus Orchards in Hunan Province**

Soil pH plays a crucial role in determining the solubility and availability of soil mineral nutrients. The soil pH values from 5.5 to 6.5 are considered as the optimum range for citrus crops (Lu et al., 2002). Acidic soils may limit the plant growth and nutrient absorption capability of the roots (Long et al., 2017). Actually, soil acidification in citrus orchards occurs universally in the main citrus producing areas including Hunan Province (Cao et al., 2019), Guangdong Province (Hong et al., 2017) and Fujian Province (Li et al., 2015). In this study, the average soil pH value in Hunan citrus orchards was found to be below the optimum range, and there were 60.2% of sweet orange orchards and 35.8% of mandarin orchards showing average soil pH values even lower than 4.8. Soil acidification in Hunan citrus orchards attributed to long-term application of chemical fertilizer, low input of organic fertilizer and less attention on soil improvement and orchard management in past decades (Guo et al., 2018; Yang et al., 2020; Zhu et al., 2020). To alleviate soil acidification, lime is generally used to increase the content of calcium (Ca) so as to neutralize the soil acidity (Anjos, Sobral, and Junior 2011; Obreza and Morgan, 2008). However, long-term application of lime increases soil pH but impairs nutrient absorption of plants. For example, lime-induced Fe chlorosis frequently occurs in citrus trees under lime application (Mattos et al., 2020). Fused calcium-magnesium-phosphate fertilizer is an alkaline and mineral fertilizer, which could be a good soil conditioner (He et al., 2019; Zhou et al., 2019). And now in the industry, it has been an integrated method to use both calcium-magnesium-phosphate fertilizers and organic fertilizers to improve the original soil in citrus orchard establishment. Hence,
fused calcium-magnesium-phosphate fertilizer could be an option for citrus orchards to mitigate soil acidification.

Soil quality is affected by soil structure and farming system and OM plays a critical role in determining soil quality. The results showed that there was sufficient soil OM in 96.7% of sweet orange orchards and 95.9% of mandarin orchards, which may be ascribed to the following two reasons. Firstly, many citrus orchards were established in paddy fields in recent decade, where there was high basic OM; secondly, with the advocacy of organic fertilizer instead of chemical fertilizers in recent years, many citrus orchards started to improve soil OM by adding organic fertilizers, crop residue, animal manure or biochar (Lin et al., 2019; Zhang et al., 2018). OM promotes soil quality and facilitates the release and absorption of essential nutrients by providing cation exchange sites and acting as the reserve of N and P (Tarrason et al., 2007). Besides the essential elements, the utilization efficiency of micro-nutrients such as Cu, Mn and Zn is also closely associated with soil texture and OM content (Mattos et al., 2020), which could explain the positive correlations between soil OM and alkaline N, available P, available K and most micro-element nutrients in both sweet orange orchards and mandarin orchards (Figure 4). Therefore, the use of organic fertilizer combined with essential mineral elements in citrus production can not only provide primary nutrients but also improve the soil structure and quality. Based on these results and the field practice, application of organic fertilizer in the orchards before winter to recover and enhance tree vigor should be strongly recommended in citrus production.

The distribution frequency of macro- and micro-elements was generally consistent between sweet orange and mandarin orchards. The soils in most citrus orchards were deficient in alkaline N, available P, available K and available B, but rich in available Fe, available Mn and available Cu, and had appropriate levels of available Zn. Citrus plants require large amounts of N, P and K, which are critical for plant growth, production and fruit quality. In previous studies, the recommended N, P and K application amounts were 200 to 350 kg/ha/year (yr), 100 to 200 kg/ha/yr, and 100 to 250 kg/ha/yr, respectively (Alva et al., 2006a; Kadyampakeni et al., 2016; Lei et al., 2019). Our results showed that nearly half of the sampled citrus orchards were deficient in soil alkaline N, and 15.8 to 22.6% of citrus orchards showed low levels of soil alkaline N, which is probably due to the following reasons. Firstly, the development of citrus plants including the fruit could deplete soil N, in which 1.2 to 1.9 kg N would be exported for each ton of harvested fresh fruit (Mattos et al., 2020). Secondly, leaching should be another cause (Martinez et al., 2002; Mattos et al., 2003), particularly in Hunan Province with annual rainfall of 1400 to 1600 mm.

Growth of citrus plants and fruit harvest also take P and K away from the soil (Mattos et al., 2020). P is easily fixed in the soil, and the available P may vary greatly due the differences of soil structure and properties (Rodrigo et al., 2016). Although the overall average levels of P and K in the studied orchards were within the optimum range, over 40% orchards showed deficiencies in soil P and K (Table 1). Great variations in soil P and K contents indicate complex soil conditions in individual orchards and irregular fertilizer managements among smallholder orchards.

Available Fe can be more readily dissolved in acidified soils, which will in turn aggravate soil acidification (Fan et al., 2015). High content of soil Fe should be associated with the low soil pH in Hunan citrus orchards (Table 1), and wide application of mancozeb as a broad-spectrum fungicide in citrus diseases control would be the cause of richness of Mn and Zn (Huang et al. 2021a; Zhang et al., 2019). Boron plays an important role in citrus yield and productivity (Zhang et al., 2015). In this work, more than 60% of citrus orchards showed low levels of soil available B, suggesting a universal B deficiency in Hunan citrus orchards. With many small orchard holders, shortage of B supplementation in orchards probably contributes to B deficiency (Wang et al., 2018).

Overall, the use of calcium-magnesium-phosphate fertilizer combined with organic fertilizer could be a good option to alleviate soil acidification and improve soil quality in Hunan citrus orchards.
Depending on individual orchard management, more attention should be paid to soil NPK and B in this area.

**Nutrient Conditions of Citrus Plant in Hunan Province**

Analysis of leaf nutrients is more effective for perennial horticulture crops (Li et al., 2018). N and K are required in many physiological processes including vegetative and reproductive growth, resulting in high uptake and assimilation of them in citrus plants (Alva et al., 2006a, 2006b; Kadyampakeni et al., 2016). Additionally, the absorption rate of N and K by plant growth is faster than the release rate of N and K from the soil (Al-Qurashi et al., 2015). The results in this study showed that N and K deficiencies occurred universally in not only soils but also leaves in most Hunan citrus orchards, indicating that supplementation of N and K fertilizer should be highly recommended in this area.

Boron and Zinc play crucial roles in citrus photosynthesis (Han et al., 2008; Srivastava and Singh, 2009), fruit quality and yield (Camacho-CristoBal et al., 2008). Foliar application of B and Zn may be an effective way to increase their contents in citrus plants, which will help to promote the vegetative growth, yield and fruit quality (Boaretto et al., 2011). Our results showed that leaf B and Zn were extremely deficient in sweet orange and mandarin orchards (Table 3). The deficiency of leaf B was obviously linked with its deficiency in soils (Table 1). For Zn, it was approximately at the optimum level in the soil while there was less available Zn in plants, which is possibly due to the weak mobility and high fixation of Zn in soils (Razzaq et al., 2013). Overall, the deficiency of B and Zn in leaves is a prominent problem in Hunan citrus orchards. Cu is indispensable for carbohydrate and nitrogen metabolism (Huang et al., 2021b; Li et al., 2019; Silva-Stenico et al., 2009) and fruit quality. However, excessive Cu will increase the production of reactive oxygen species (ROS) (Ravet and Pilon, 2013), which will cause the degradation of protein and enzyme to affect cellular biochemistry and inhibit plant growth (Yruela, 2009). In this study, 36.6% of mandarin orchards and 64.8% of sweet orange orchards exhibited excessive leaf Cu (Table 2), which is probably associated with the control of citrus canker disease that involves the universal use of copper bactericides like Bordeaux mixture (Behlau et al., 2010). Actually, sweet oranges are more susceptible to citrus canker than mandarins, which means a possibly uneven application of copper bactericides in orchard management.

Citrus uptakes nutrients from soil, assimilates and stores part of them in plants and then redistributes them to organs such as leaves, flowers and fruits (Roccuzzo et al., 2017). The results in this study suggested that the N: P: K ratio in citrus fruit was close to 1:0.14:0.6, which is consistent with the recommended citrus NPK fertilization of high N, medium K and low P (Lei et al., 2019). Considering the low demand of P by citrus crops and its high fixation in soil (Huang et al., 2019), a low level of P supplementation or supplementation every two years may be a good option in citrus orchards.

**Correlations between Soil Nutrients, Leaf Nutrients, Fruit NPK and Quality Parameters**

Evaluation of the correlations among soil, leaf and fruit nutrients may allow the establishment of optimal fertilization management in citrus production. From our data, only several leaf nutrients (N and Mo in mandarins, Mn in sweet oranges and Zn in both types) were significantly correlated with the corresponding soil nutrients (Figure 4). Leaf K was positively correlated with fruit K, suggesting a high requirement and flux of K from the leaf to the fruit. Soil Mo was significantly correlated with NPK, Zn and Cu in leaves. As previously reported, most soil nutrients have no high correlations with leaf nutrients in citrus orchards (Li et al., 2015; Yu et al., 2007; Huang et al., 2001; Tang et al., 2013). Generally, citrus leaf nutrients are not linearly related to soil nutrients possibly due to the following reasons. 1) As a perennial crop, citrus plant stores a large amount of nutrients in older leaves, stems and roots (Mattos et al., 2003, 2020). 2) Uptake of mineral elements not only depends on the amount in soil, but also is affected by many factors such as nutrient use efficiency (Obreza and Morgan, 2008),
soil physicochemical properties (Vashisth and Kadyampakeni, 2020), and fertilization method (Ruan et al., 2019).

Citrus fruit quality is of particular concerns in many countries due to fresh consumption. Obviously, fruit quality is highly influenced by orchard fertilization management. It is generally accepted that leaf NPK is positively correlated with fruit yield and quality (Alva et al., 2006a; Mostafa and Saleh, 2006). The results of this study indicated that citrus FFW is highly correlated with leaf NPK (Table 4), suggesting the importance of NPK fertilization in citrus yield. Consistent with the finding that P supplementation contributes to plant growth and fruit yield (Quaggio et al., 2006), leaf P was found to greatly contribute to the FFW, TSS and TSS/TA in this study (Table 4).

Conclusion
The findings of this study suggest that Hunan citrus orchards are characterized by low soil pH and rich soil OM. Most orchards are imbalanced in nutrition with universal deficiency in soil NPK and B and leaf N, K, Zn and B. Excessive Fe, Mn and Cu are present in soils and leaves of both citrus types. The accumulation of fruit NPK is close to a ratio of about 1: 0.14: 0.6, and leaf K is significantly correlated with fruit K in citrus crop. In terms of fruit quality, leaf P markedly affects the FFW, TSS, TS and TSS/TA, and leaf NPK and Mo have great impacts on fruit FFW and TSS. The combination of calcium-magnesium-phosphate fertilizer and organic fertilizer is recommended to cope with the universal soil acidification in Hunan citrus orchards. Supplementation of N, K, Zn and B should be emphasized in Hunan citrus orchards in case of further symptoms.

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