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Integrated Nutrient Management Significantly Improves Pomelo (*Citrus grandis*) Root Growth and Nutrients Uptake under Acidic Soil of Southern China

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Abstract: Root system plays a crucial role in plant growth and development by uptake of soil nutrients, which is affected by intensive use of NPK fertilizer. However, it is unknown how integrated nutrient management (INM) could affect the root growth and its nutrient uptake in the red soils of southern China. For this, the impacts of different INM practices on root morphological traits and root nutrient uptake were investigated in the pomelo tree. First, we investigated the spatial root distribution of various tree ages (i.e., 8, 13, 18, and 23 years old) and found the optimum root growth at 20–80 cm around the tree trunk in topsoil (0–20 cm). Hence, the pomelo trees were fertilized at 20–80 cm around the trunk, i.e., FFP (farmer fertilization practice), optimization NPK fertilizer (O) combined with lime (L) and mushroom residue (M) known as O+L+M treatment, and O+L combined with Mg fertilizer called as O+L+Mg treatment. We found that root length (RL) significantly increased by application of O+L+M (108.5 and 219.1 cm) and O+L+Mg (73.6, 66.8 cm) in topsoil and subsoil, respectively, in 2019. Similarly, root surface area (RSA) was significantly higher under INM, i.e., O+L+Mg > O+L+M > FFP. For root diameter (RD), O+L+M (0.8 mm) and O+L+Mg (1.5 mm) showed significantly lower diameter than FFP (2.54 mm). The root tips (RT) also improved considerably under INM practices compared with FFP. Besides, root nutrient contents (N, P, K, Ca, and Mg) also significantly improved under O+L+M and O+L+Mg over FFP. Similar trends of root growth and nutrients uptake were recorded in 2020. Overall, these findings suggest that INM plays a significant role in root development and nutrient uptake under acidic soil, which could be useful for maximizing crop productivity.

Keywords: root distribution; integrated nutrient management; root traits; root nutrients; acidic soil

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1. Introduction

Citrus is one of the world's major fruit crops with global availability in over 140 countries, and China is one of the leading citrus-producing countries with an annual citrus production of 4406 × 10^4 tons [1,2]. Pomelo (*Citrus grandis*) is the third major type of citrus after *Citrus reticulata* and *Citrus sinensis* in China, with an average yield of 320 × 10^4 tons [3]. Pinghe County (Fujian Province, China) is recognized as the most famous area for pomelo production [3–5]. However, the long-term intensive or unbalanced fertilization has caused severe problems in the pomelo orchard, e.g., a decline in soil pH and Mg deficiency, etc. [6,7]. The root growth in acidic soils (pH < 4–4.5) is inhibited by Al^{3+} toxicity with adverse effects on crop production [8]. Therefore, balanced fertilization is very important for pomelo orchards to develop the most suitable soil conditions for root growth.

Recently, more emphasis has been given to the balanced fertilization strategy by reducing the usage of mineral fertilizers to improve crop quality, production, and uptake of nutrients [9]. The mineral fertilizers, especially nitrogen, phosphorus, and potassium, are essential for plant nutrition [10–12] and crop productivity [13,14]. However, an inappropriate or extensive application of fertilizers leads to severe problems of soil acidification [7,15], soil and water pollution [16,17], and greenhouse gas emissions [18,19]. Moreover, it leads to excessive and sudden plant growth with an insufficient root system to provide adequate mineral nutrients and water supply to the plant. Thus, the poor root structure results in reduced flowering and fruit production, leading to poor plant growth [20]. Furthermore, with the increasing cost of chemical fertilizers and growing concerns over the environmental impact of excessive fertilization, there has been increasing scrutiny on how nutrients should be managed on farms [21]. Hence, the selective and appropriate use of substrate is a crucial factor for high production.

Integrated nutrient management (INM) aims for optimal soil fertility and plant nutrition, increasing fertilizer input efficiency, decreasing environmental risks, and improving crop productivity through root/rhizosphere management [9]. Various models have been presented for sustainable soil management to increase the yield and produce nutritious and healthy products [22,23]. Regarding management methods, the application of organic and inorganic sources of nutrient elements has been used to obtain optimum productivity [9]. Therefore, finding innovative integrated nutrient management is a matter of great interest that could offset soil acidification and provide a healthy soil environment for plant roots to uptake the soil nutrients efficiently.

The root system plays an imperative role in crop yield because it performs essential functions for the plant, including water uptake, nutrients acquisition, and anchoring into the soil system [24,25]. It has been found that changes in the soil microenvironments (e.g., soil moisture, temperature, fertility, mechanical strength, and soil porosity, etc.) affect the growth of plant roots [26]. Various studies on the horticultural and agricultural systems have revealed how organic and inorganic amendments affect plant growth and root morphological characteristics [27,28]. However, research on the effects of N.P.K fertilizers amendments with lime, mushroom extract, and Mg fertilizer on tree growth, particularly on root morphological traits, is rare. Lime is recognized as an effective measure to improve the soil pH and has a beneficial effect on root growth [29]. It has also been found that mushroom residue improves soil structure and has a substantial impact on increasing soil pH. However, Mg deficiency usually occurs in the acidic soils of China because a decrease in soil pH is coupled with deficiencies in soil exchangeable Mg [30,31]. Therefore, it would be of great interest to investigate the combined effects of NPK fertilizer with lime, mushroom residue, and Mg fertilizer on root growth. Thus, measurement of root morphological traits such as root length, root surface area, root diameter, etc. are indispensable to broaden the understanding of plant physiological functions. For instance, root length is considered as the most important indicator that controls the water and nutrients acquisition, as well as the primary indicator of plant response to changing environmental conditions [32,33], whereas, root diameter is the beneficial indicator for the increase in biomass [34]. Hence, the knowledge of rooting patterns is an important aspect of crop production because it gives background information for the efficient use of fertilizer. Consequently, root traits have always been a critical target for researchers and breeders for crop improvement.

So far, analyzing the root phenotype is particularly important for understanding the response of root characteristics to nutrient management and developing precise agricultural practices in the future. Therefore, the present study was aimed at comprehensive nutrient management for pomelo orchards prone to soil acidification to develop the most suitable soil conditions for root growth. However, to the best of our knowledge, this study, for the first time, investigated how INM based on inorganic N.P.K fertilizer combined with lime, mushroom residue, and Mg may affect the root growth and nutrients availability in the root system. We hypothesized that fertilizers reduction input plus lime, mushroom residue, and Mg application could construct a more reasonable root architecture in pomelo.

Therefore, a two-year field experiment was conducted to compare the effects of INM with conventional nutrient management. The key objectives were (1) to investigate the impact of different INM on root morphological traits and (2) to identify the influence of varying INM on nutrient uptake via roots.

2. Materials and Methods

2.1. Study Area

Guanximiyou pomelo (*Citrus grandis*) orchard of Pinghe County (24°02′–24°35′ N, 116°54′–117°31′ E) located in the southern region of Fujian Province, was selected for this study. This area is characterized by a subtropical monsoon climate with average annual precipitation of about 1600–2000 mm, temperature 17.5–21.3 °C. The soil type of this study area is classified as haplic ferralsols that are classified as red soil in the Chinese soil classification system and contains 39.2% sand, 35.8% silt, and 25.1% clay [35]. The basic soil properties are shown in Table 1.

Table 1. Soil physicochemical properties of the pomelo orchard (means ± standard deviation, n = 3).

Soil Depth (cm)	pH	Nitrate-N (mg/kg)	Ammonium-N (mg/kg)	Available-P (mg/kg)	Available-K (mg/kg)	Exchangeable-Ca (mg/kg)	Exchangeable-Mg (mg/kg)
0–20	4.6 ± 0.4	11.0 ± 3.1	45.7 ± 14.8	787.6 ± 94.5	341.0 ± 87.8	294.4 ± 159.8	92.8 ± 37.1
20–40	4.2 ± 0.4	6.0 ± 1.8	32.3 ± 22.1	509.9 ± 116.0	252.9 ± 54.7	260.0 ± 121.0	63.4 ± 26.1

2.2. Pomelo Root Spatial Distribution Survey and Analysis

To check the spatial distribution of pommel root, we selected trees of different ages, i.e., 8, 13, 18, and 23 years old. Root samples were collected horizontally at 20, 40, 60, 80, 100, 120, and 140 cm away from the tree trunk at 0–20 and 20–40 cm soil depth vertically (Figure 1). Eight trees were selected for each age of the tree, and samples were collected using a soil core sampler (3 cm diameter). To reduce the plot damage, a borehole sampling method was used to collect the pomelo roots [36]. The roots were washed with deionized water and scanned with the scanner (Epson V800, China, Co., Ltd., Beijing, China). Root images were analyzed using WinRhizo software (Regent Instruments Inc., Quebec, QC, Canada) for diffident root morphological traits, including root length density (RLD), root surface area (RSA), and root diameter (RD).

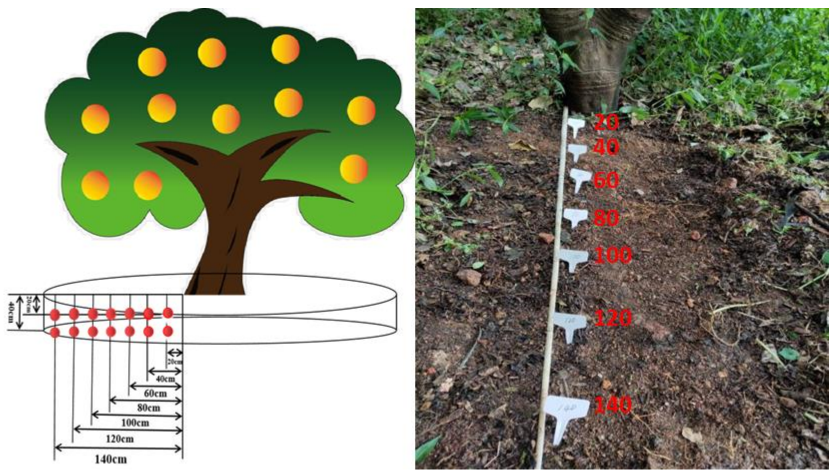

Figure 1. Collection of root samples for spatial distribution. The root samples were collected vertically from 0–20 cm and 20–40 cm soil profiles. For horizontal spatial root distribution, root samples were collected from 7 soil layers (0–140 cm, each at 20 cm interval) around the tree trunk.

2.3. Experimental Setup and Harvest

As a result of the spatial root distribution survey, the pomelo trees were fertilized around 20–80 cm from the trunk for two consecutive years, i.e., 2019 and 2020. Based on different growth periods of pomelo, fertilization was applied at four different stages, i.e., February (shooting and flowering stage), April (fruit stabilizing stage), June (fruit expansion stage), and December (Table S1). For fertilization, we set up three treatments: (1) farmer fertilization practice (FFP), (2) optimization of N.P.K (O) by reducing the input, and combined with the application of lime (L) and mushroom residue (M) to control soil pH, and called O+L+M treatment, (3) combination of Mg fertilizer with O+L called as O+L+Mg. The lime used in this study was hydrated lime, i.e., $Ca(OH)_2$, in the form of fine powder. It is used to neutralize the soil acidity to obtain a desirable soil pH that supports plant growth. It was applied around the tree trunk at 20–80 cm (Figure S1). The mushroom residue was the waste material left after the production of mushrooms and obtained from Xiamen Jiangping Company, and chemical composition has been shown in Table S2. These were applied around the tree trunk at 75–125 cm in FFP, while at 20–80 cm in O+L+M (Figure S2). The fertilizers used in this study included urea (46% N), diammonium phosphate (42% P_2O_5), potassium sulfate (51% K_2O), lime (75% CaO), and magnesium sulfate monohydrate (27.5% MgO). The fertilizer application rate is shown in Table 2.

Table 2. The application of fertilizers (kg/ha).

Treatment	N	P_2O_5	K_2O	MgO	Lime	Mushroom Residue
FFP	1084	914	906	0	0	7700
O+L+M	160	0	176	0	3108	2000
O+L+Mg	200	0	200	40	3108	0

Root samples were collected horizontally 50 cm away from the tree trunk at vertical 0–20 and 20–40 cm soil depth in June 2019 and 2020. The root samples were collected from two trees of each plot and composited as a representative sample for each treatment. Three plots were selected for each replication. The borehole sampling was deployed to obtain the pomelo root samples to minimize plot damage [36]. The roots were scanned with Epson V800, after being cleaned with deionized water. Root images were analyzed using WinRhizo software (Regent Instruments Inc., Quebec, QC, Canada) for diffident root morphological traits, i.e., root length (RL), root surface area (RSA), root diameter (RD), and the number of root tips (RT).

2.4. Determination of Root Nutrient Contents

The root samples were oven-dried (70 °C, 48 h), and dry biomass was recorded. Root N, P, K, Ca, and Mg were extracted and measured according to the following Bao (2000) protocol [37]. For N, P, K, 0.05 g of the ground root sample was weighed and transferred to the digestion tube and 5 mL of concentrated sulfuric acid (H_2SO_4) and 2.0 mL of hydrogen peroxide (H_2O_2) were added. The digestion tubes were kept in the digestion block for approximately 4 h, at a temperature of 200 $\pm$ 20 °C until obtaining clear digestion without the presence of particles, and then cooled at room temperature. The digested samples were transferred to a 100 mL volumetric flask, filled with 100 mL distilled water, and stored at 4 °C in a refrigerator until nutrients determination. For Ca and Mg determination, 0.10 g of the ground root sample was weighed and transferred to the conical flask, and 12 mL of nitric acid (HNO_3): perchloric acid ($HClO_4$) in ratio 5:1 *v/v* was added. The digestion tubes were taken to the digestion block for approximately 3 h, at a temperature of 200 $\pm$ 20 °C until obtaining a clear digest without the presence of particles. This procedure was performed in triplicate for each sample; solutions containing all the reagents were prepared analogously to be evaluated as a blank test. Total nitrogen was determined with a Skalar Flow Analyzer. Total potassium was determined with the Flame Photometer. Total phosphorus, magnesium, and calcium concentrations in the samples were determined using an inductively coupled plasma optical emission spectrometer (ICP-OES), and these solutions were filtered through a 0.4 μm filter membrane before analysis.

2.5. Statistical Analysis

One-way analysis of variance was performed to analyze the effect of different treatments on root morphological traits. A *t*-test was performed to check whether root traits at different soil depths differed from each other. We performed the least significant difference ($LSD_{0.05}$) test to analyze the difference between the treatments using the SPSS 25.0 software (International Business Machines Corporation, New York, NY, USA).

3. Results

3.1. Dynamic Spatial Root Distribution

Root length density (RLD) showed significant spatial distribution patterns along with a horizontal soil profile and decreased significantly with increasing distance from the trunk for all ages. Overall, RLD was much higher in 0–80 cm than 140 cm (FFP), and FFP exhibited low root length density. Moreover, we found that RLD in the topsoil (0–20 cm) was much higher than in the subsoil (20–40 cm) (Figure 2a). Similarly, the horizontal spatial distribution of roots distribution also significantly affected the root surface area (RSA) for all tree ages. We found that RSA decreased with increasing distance from the trunk and showed the maximum RSA closer to the trunk (20–80 cm). Like RLD, the minimum RSA was recorded at a sampling point of 140 cm, suggesting the poor reliability of farmer practice. Besides, the average RSA was higher in the topsoil over subsoil (Figure 2b). Root diameter (RD) was also significantly affected along with the horizontal spatial distribution. RD was substantially higher closer to the trunk at 0–80 cm and then gradually decreased and minimum RD was recorded at the 140 cm sampling point. Overall, the RD was higher in the topsoil compared with the subsoil (Figure 2c). Thus, root development along spatial distribution was much better in the 20–80 cm from the trunk and also in the topsoil of 0–20 cm (Figure 2d).

3.2. Root Morphological Traits under Various Nutrients Management Practices

The findings of the present study showed that INM significantly promoted the root morphological characteristics. Under different nutrient management practices, including O+L+M and O+L+Mg, the roots' morphological traits improved significantly, i.e., root length (RL), root surface area (RSA), root diameter (RD), and root tips (RT) compared with farmer fertilizer practice.

RL was significantly ($p \leq 0.05$) increased under O+L+M and O+L+Mg treatments compared with FFP along with vertical soil profile during 2019 and 2020 (Figure 3a). RL under the FFP was 28.97 and 28.75 cm, and it was significantly increased by the application of O+L+M (108.48 and 219.14 cm) and O+L+Mg (73.58, 66.81 cm) for topsoil (0–20 cm) and subsoil (20–40 cm), respectively, in 2019. Similar results were found during the preceding year-2020, and significant RL improvement was recorded (Figure 3a). The INM significantly ($p \leq 0.05$) influenced the RSA, and O+L+M and O+L+Mg showed excellent results compared with FFP, i.e., O+L+Mg > O+L+M > FFP. RSA in the topsoil was 7.98, 26.72, 66.68 cm^2 for the year 2019, while 54.48, 161.65, and 203.17 cm^2 in 2020, at FFP, O+L+M, and O+L+Mg, respectively. Furthermore, the spatial distribution of roots showed a relatively higher average RSA in the topsoil compared with subsoil during 2019 and 2020 (Figure 3b). For average RD, the pomelo trees treated with O+L+M (0.81 mm) and O+L+Mg (1.49 mm) reduced their diameters significantly compared to FFP (2.54 mm) in the topsoil during 2019, and a similar trend was recorded for subsoil in the year 2020. The roots ≤ 2 mm in diameter have greater ability to uptake the nutrients. Hence, average RD was significantly decreased under the O+L+M and O+L+Mg (Figure 3c). Similar to RL, RSA, and RD, the RT was also improved considerably under the O+L+M and O+L+Mg treatments compared with FFP along with vertical soil profile during 2019 and 2020, but the maximum number of RT was found in the topsoil during both years (Figure 3d). Overall, these results imply that nutrient management practices had a significant effect on root development, especially in the topsoil compared with FFP.

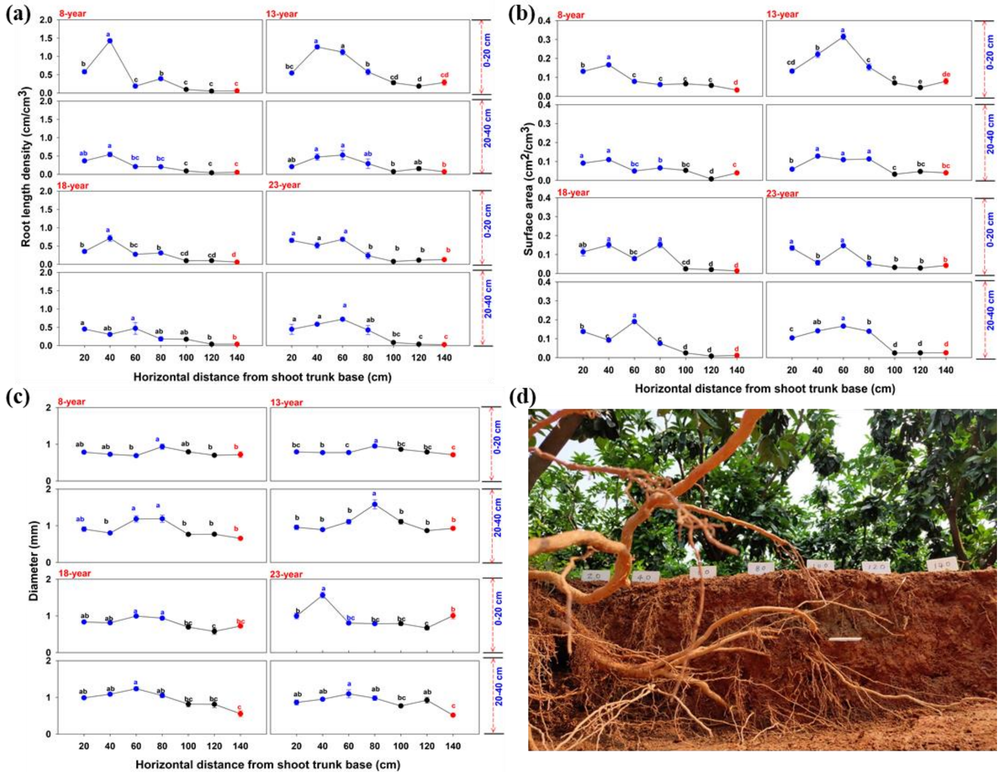

Figure 2. Spatial distribution of pomelo root growth under different tree ages. (**a**) Root length density; (**b**) root surface area; (**c**) root diameter, along the horizontal (20–140 cm) and vertical (0–20, 20–40 cm) soil profile. The red dot at 140 cm is showing the farmer fertilizer practice zone of fertilizer application. Significant differences ($p < 0.05$) among different horizontal sampling points are shown by different letters, $n = 8$; (**d**) Overall distribution pattern of pomelo root growth concentrated in 20–80 cm.

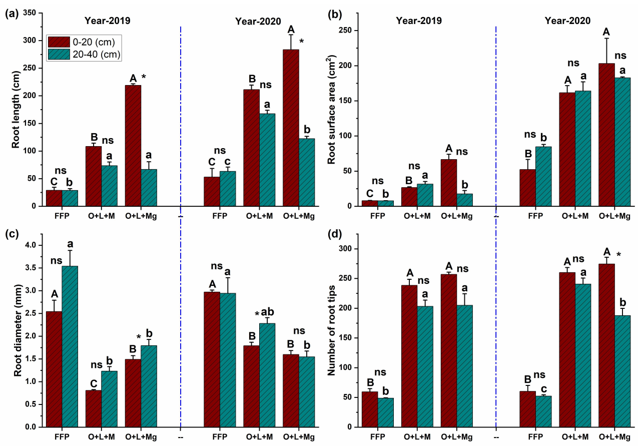

Figure 3. Root morphological traits under different nutrient management. (**a**) Root length; (**b**) root surface area; (**c**) root diameter; (**d**) root tips, along with the vertical soil profile, i.e., 0–20 and 20–40 cm during 2019 and 2020. The alphabetic letters on the bars indicate a significant difference ($LSD_{0.05}$). The error bars represent the standard deviation of the mean ($n = 3$). The upper-case letters denote the significant differences for different treatments at 0–20 cm, while the lower-case letters for 20–40 cm depth. The significant differences between the topsoil (0–20 cm) and subsoil (20–40 cm) are indicated by the symbol *, while ns denotes the non-significant differences ($n = 3$).

3.3. Root Nutrient Contents

Compared with the FFP treatment, the O+L+M and O+L+Mg treatments significantly increased the N, P, K, Ca, and Mg contents in pomelo roots. In the O+L+M and O+L+Mg treatments, the reduced input of N, P, and K did not minimize root nutrient contents, while the root nutrient contents of N, P, K, Ca, and Mg increased significantly.

In 2019, root nutrient contents in topsoil were increased compared with the FFP, e.g., the total amount of N was increased 32.32% and 242.95%, P was increased 64.07% and 187.76%, K was increased 110.62% and 8.02%, Ca was increased 89.97% and 158.37%, and Mg was increased 239.51% and 85.49% for O+L+M and O+L+Mg treatments, respectively. Similarly, at 20–40 cm, root nutrient contents were also increased in O+L+M and O+L+Mg treatments compared with FFP. Root nutrient contents at a soil depth of 0–20 cm were higher on average by 1.5% compared to 20–40 cm. In 2020, the root nutrient contents were significantly increased for N 23.13% and 198.61%; P was increased 139.10% and 74.89%, K was increased 19.10% and 60.85%; Ca was increased 44.49% and 32.96%, and Mg was increased 97.57% and 35.45% under O+L+M and O+L+Mg treatments, respectively, compared with FFP treatment. Hence, the INM increased the root nutrient contents by 60% on average, while root nutrient contents at 0–20 cm were 1.8% higher than 20–40 cm (Figure 4). It implies that the nutrient management (O+L+M and O+L+Mg) showed better results than FFP and also more root nutrient contents at 0–20 cm than 20–40 cm. The INM significantly increased the root nutrient content, indicating that nutrients were fully utilized, and hence improved the nutrient availability under pomelo orchard.

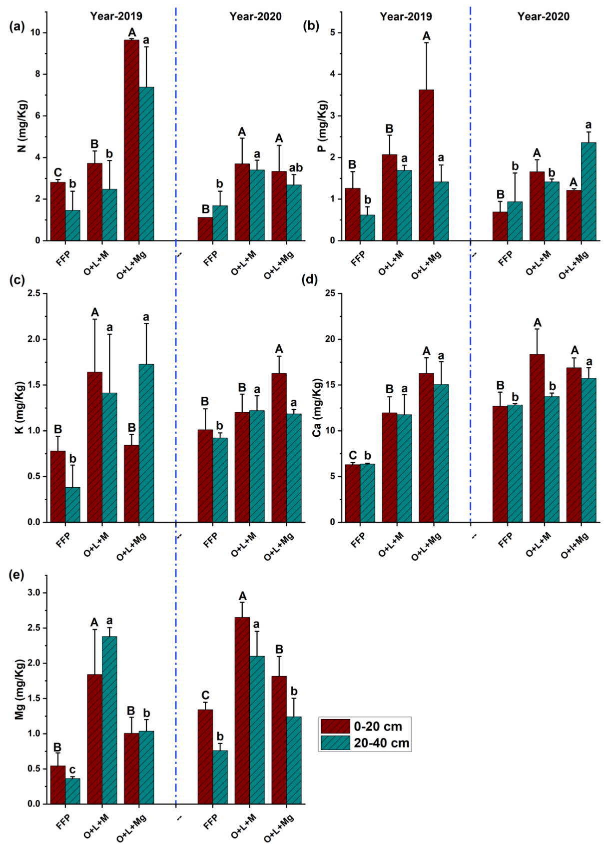

Figure 4. Nutrient management effects on root nutrient contents. (**a**) Nitrogen (N mg/kg). (**b**) Phosphorous (P mg/kg). (**c**) Potassium (K mg/kg). (**d**) Calcium (Ca mg/kg). (**e**) Magnesium (Mg mg/kg) along with the vertical soil profile, i.e., 0–20 and 20–40 cm during 2019 and 2020. The alphabetic letters on the bars indicate a significant difference ($LSD_{0.05}$). The error bars represent the standard deviation of the mean (n = 3). The upper-case letters denote the significant differences for different treatments at 0–20 cm, while the lower-case letters for 20–40 cm depth.

3.4. Relationship between Root Nutrient Contents and Morphological Traits

The root nutrient contents of N, P, K, Ca, and Mg were generally positively correlated with root morphological traits, i.e., RL, RSA, and RT, while negatively correlated with RD during both 2019 and 2020 along with vertical soil profile of 0–20 and 20–40 cm (Figure 5).

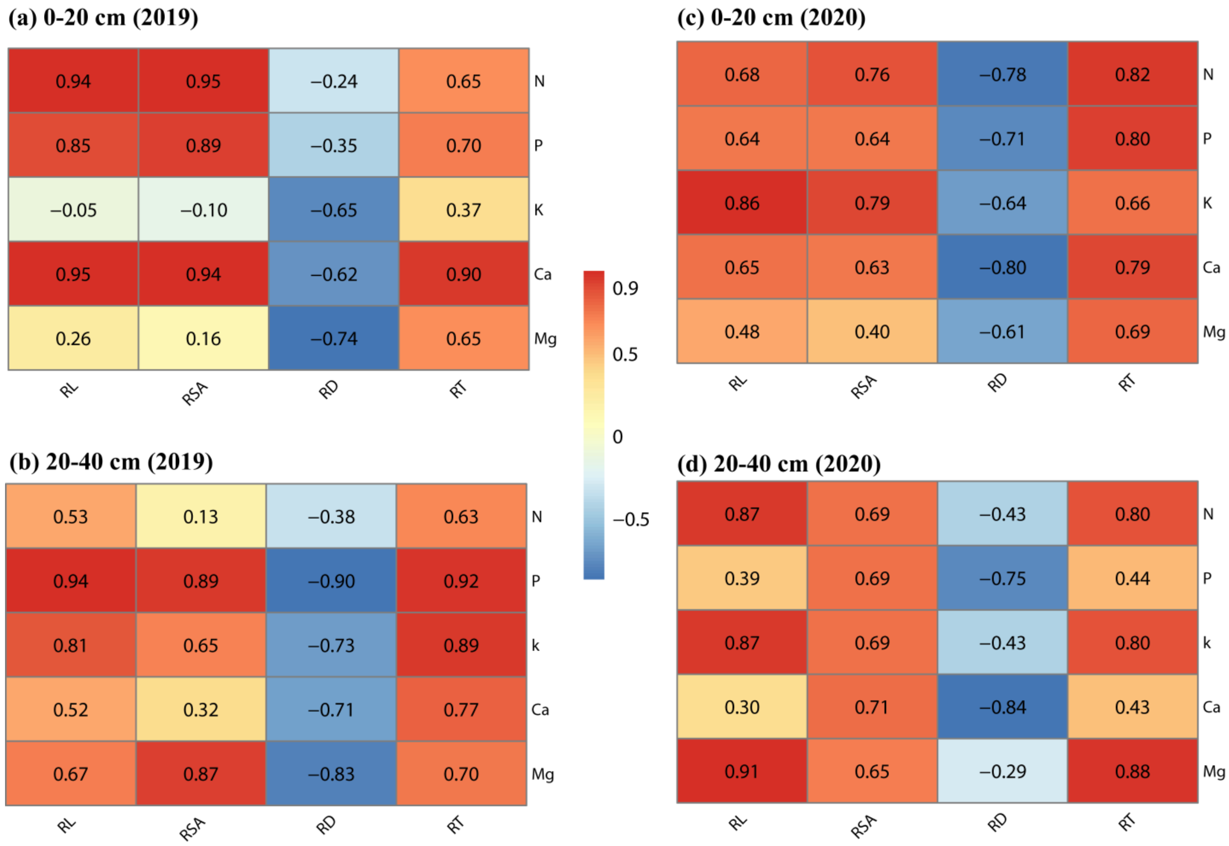

Figure 5. Linear correlation between root traits and nutrient contents. The correlation analysis was studied; (**a**,**b**) Year-2019 at 0–20 and 20–40 cm; (**c**,**d**) Year-2020 at 0–20 and 20–40 cm, between root morphological traits root length (RL), root surface area (RSA), root diameter (RD), root tips (RT), and root nutrient contents nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg). The values indicate the correlation coefficients.

4. Discussion

Roots serve as the linkage between soil particles and plants, and their development has a substantial impact on plant nutrition [38]. Various studies imply that root morphological traits have a crucial influence on soil nutrient absorption [39–41]. As a consequence, understanding root development and dynamics are critical for determining the most effective nutrient management practices, allowing plant roots to absorb the nutrients efficiently and resulting in better plant growth [42,43]. Therefore, we conducted a systematic study in which first we assessed the development of pomelo root growth, and then based on the initial survey, we identified the impact of various nutrient management practices on root morphological characteristics and its nutrient absorption.

Plants can be fertilized either directly or indirectly; nevertheless, adequate amount, timing, area, and distribution of fertilizer are of prime importance [38,44–46]. In Pinghe county, we found that extensive application of N.P.K fertilizer at 75–125 cm away from the trunk (farmer fertilizer practice) resulted in various soil constraints, e.g., soil acidification (low pH) that influences the nutrient's availability to the plants [46,47]. Therefore, in this study, first we surveyed the distribution of pomelo root growth and found that root growth was concentrated horizontally at 20–80 cm away from the trunk and vertically along 0–20 cm soil profile (Figure 2). Our results are in line with the previous findings of horticulture fruit trees of pear and citrus, suggesting that 86% of root growth was located at the horizontal distance of 80 cm [48–50] and vertically concentrated in the upper 15 cm [51,52]. This might be owing to more nutrient availability in these soil layers due to more active biological cycling, and hence root growth is improved and provides more nutrients to the plant [53]. Thus, to check the effectiveness of different nutrient management practices, we reduced the N.P.K fertilizer and integrated it with lime, mushroom residue, and Mg, e.g., O+L+M and O+L+Mg treatments, and we identified the impact on root traits.

As expected, the nutrient management (O+L+M and O+L+Mg) improved the root growth traits (RL, RSA, RD, and RT) (Figure 3) and also root nutrient uptake (Figure 4) compared with FFP under acidic soils. The acidic soils are characterized by high soil acidity and low soil fertility [54], and soil acidification is one of the limiting factors that restrict plant growth and development in south China [55]. Therefore, we used the lime and mushroom residue to control the soil pH because it has been reported that liming with fertilization significantly improves the exchangeable Ca^{2+} and Mg^{2+}, while decreasing the exchangeable Al^{3+} [56,57] and promoting the absorption of nutrient elements in the pomelo trees in the topsoil [58–60]. Our results agree with those of Hailing et al. (2010), who affirmed liming with fertilization improves the root morphological traits [56,57,61]. Besides, the mushroom residue also significantly improved the root architecture of the pomelo tree and this is consistent with previous findings [62,63]. Mushroom residues contain a significant number of essential nutrients for plant growth that have been reported in previous studies [64,65], and they improve the soil organic matter, quality, and pH [15,63]. Consequently, better nutrient availability resulted in improved root morphological traits under various nutrient management practices and could play an important role in increasing the pomelo yield under acidic soils of southern China.

Mg is primarily absorbed by plants through their root system, and its availability is significantly influenced by soil acidification, e.g., a decrease in soil pH is coupled with deficiency in soil exchangeable Mg [66,67]. However, its mobility is susceptible to leaching in the soil profile, especially in the acidic soil with high precipitation [68]. It has been reported that liming eliminates the detrimental effects of soil acidification and improves the Mg availability and Mg fertilizer use efficiency [69]. Mg application into the soil is thought to be an effective nutrient management practice to improve the soil Mg concentration due to its vital role in photosynthesis, plant growth, and root traits [70]. We found that Mg application significantly improved the pomelo root growth and nutrient uptake. These results are similar to previous findings where the application of Mg significantly improved the root morphological attributes [71–73]. It could be explained that Mg fertilizer may improve chlorophyll synthesis and result in glucose production. So, these biochemical attributes are utilized by the plant roots in the respiration process. As a result, root growth traits (root length and root surface area) are improved and facilitate the nutrient uptake by roots in plants [74]. Root length is indeed one of the most frequently measured parameters, primarily due to its significance as a general, standardized predictor of plant response to environmental factors [33], because of its role in the transport of nutrients and water [32]. In addition, we found that root diameter (<2 mm) decreased under integrated management practices, and it has been well established that roots <2 mm favor the higher respiration rate [75], which favors the improved root growth and nutrient uptake [74]. The root surface area and root tips improved under INM possibly due to the synthesis of biochemical attributes under efficient nutrient uptake by roots and were supposed to be favorable for biomass production [34,74]. Hence, these root traits could not be improved under severely Mg deficient soils. Therefore, integrated nutrient management showed significant results in improving the pomelo root growth and enhanced root nutrient availability like N, P, K, Ca, and Mg.

5. Conclusions

This study first investigated the pomelo rooting growth patterns along with vertical and horizontal soil profiles. We found that root growth was more active and concentrated at the top vertical soil profile of 0–20 cm compared with 20–40 cm, while horizontally, the root growth and development was better at 20–80 cm from the tree trunk. Thus, we applied different treatments (O+L+M and O+L+Mg) in the active root growth zone, i.e., 20–80 cm, and compared with farmer fertilization practice. We found that nutrient management, including lime, mushroom residue, and Mg fertilizer with optimized input of N.P.K fertilizers, significantly improved the root morphological traits, i.e., root length, root surface area, root diameter, and root tips compared with the farmer fertilization practice. It also resulted in improved root nutrient uptake, e.g., such as N, P, K, Ca, and Mg, and we found a positive correlation between the root morphological traits and root nutrient uptake. Therefore, the application of optimized N.P.K fertilizer combined with lime, mushroom residue, and Mg fertilizer is an effective approach in the acidic and Mg-deficient pomelo orchards to develop healthy and sustainable orchards by means of improving the root growth and its nutrient uptake. However, it is imperative to further investigate the effects of nutrient management on pomelo yield, quality, and socioeconomic benefits.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11061231/s1.

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