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Study on Soil Fertility Characteristics of Walnut Orchards with Different Parent Materials and Soil Types in Gyaca County, Tibet

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Abstract: Walnut trees on the Tibetan Plateau have sustainable and nutritious characteristics. They grow naturally without the use of any chemical fertilizers and pesticides. Therefore, the soil fertility of walnut orchards is a key factor influencing walnut yield and quality. This experiment measured and analyzed the basic soil nutrient content, microbial biomass carbon (MBC), nitrogen (MBN), phosphorus (MBP), and leaf nutrient indicators in five types of representative walnut orchard soil parent materials in Gyaca County to clarify the fertility characteristics of different soil types and their correlations with walnut nutrients, providing a basis for the sustainable development of the plateau walnut industry. The results showed that there were significant differences in soil organic matter (SOM), total nitrogen (TN), available nutrient contents, and microbial activity among soil types with different parent materials. The comprehensive representation of available nutrient levels in the soils is as follows: gray-cinnamon soil and calcareous alluvial soil > mountain meadow soil > plateau prairie soil and brush prairie soil. The average MBC, MBN, and MBP contents in the five soils were 368.8 mg/kg, 28.4 mg/kg, and 23.6 mg/kg, respectively, and the content in the topsoil (0–20 cm) was higher than that of the subsoil (20–40 cm). The total nitrogen (PN), total phosphorus (PP), and total potassium (PK) contents in walnut leaves were found to be closely related to the soil physicochemical properties and microbial activity, among which five indicators, including soil TN, available nitrogen (AN), SOM, MBC, and slowly available potassium (SAK), had the greatest impact on leaf nutrient levels. These findings are valuable for the future management and development of walnut orchards. Therefore, for different soil parent materials and soil types, improving the soil fertility and actively applying nitrogen-rich organic fertilizers should be prioritized to improve the yield and quality of Tibetan Plateau walnuts.

Keywords: nutrient content; plateau walnut; parent material; soil fertility; Tibet

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1. Introduction

China has a wide variety of walnut (*Juglans regia* L.) species, with the highest walnut production worldwide. These walnuts are mainly found in the northern thin-skinned walnut-producing areas of Shanxi, Shaanxi, Hebei, and Xinjiang, as well as in the plateau walnut-producing regions of Yunnan, Guizhou, and Tibet [1,2]. The walnut kernel is the main economic product and edible part of the walnut, and its nutritional quality and effective utilization have always been a research and development hotspot. However, the nutritional quality and yield of walnut kernels are influenced by multiple factors, including varieties, location conditions, and cultivation management, with soil fertility being the main limiting factor for walnut kernel production [3,4]. Currently, walnut production in northern regions accounts for a considerable proportion, and the soil fertility and fertilization management in these orchards is widely emphasized. The average soil organic matter (SOM), total nitrogen (TN), available nitrogen (AN), available phosphorus (AP), and slowly available potassium (SAK) contents in the soil of the main production area for Xinjiang

thin-skinned walnuts, Aksu city, are 13.5 g/kg, 0.8 g/kg, 65.2 mg/kg, 30.9 mg/kg, and 177.5 mg/kg, respectively. The soil fertility is medium, and fertilization by drip irrigation has a significant yield increase effect [5,6]. Huo et al. [7] evaluated walnut orchards in the Yunnan–Guizhou Plateau region and found that there was generally a deficiency in total potassium (TK) and AN, while the SOM and AP were abundant. Additionally, there were significant differences in soil fertility among different parent materials. In the hilly region of Shaanxi, the application of organic fertilizer and bioorganic fertilizer has been shown to increase the SOM content by 54.3–62.1% and improve the soil nitrogen (N), phosphorus (P), and potassium (K) supply capacity, as well as reduce N leaching and volatilization [8–10]. However, the evaluation and understanding of soil fertility in plateau walnuts, especially in the main production areas of Tibet, are relatively insufficient, which also limits the sustainable development of the walnut industry in Tibet.

Gyaca County, located in the southeastern part of Tibet, is situated in a broad valley area along the middle reaches of the Brahmaputra River. The cultivated land and orchards are mainly distributed along the riverbanks and in the mountainous mesas, providing a favorable ecological environment for the growth of plateau walnuts [11]. The walnut distribution area in Tibet includes two sub-areas in southern and eastern Tibet, with Gyaca County in the Shannan area and Lang County in the Linzhi area as the main producing areas. The area of walnut trees in Gyaca County is 13,266.7 ha, while that of Lang County is 2866.7 ha, and the walnut trees in this region mainly consist of a mixture of ancient tree remnants and new plantings [12,13]. The geological structure is unusually complex due to the strong uplift and elevation of the crustal movement on the Qinghai–Tibet Plateau during the late Pliocene, coupled with the undercutting and erosion effect of modern rivers. As a result, the developed mountain soil is primitive and juvenile, with low maturation, high gravel content, and poor soil fertility, while the prairie soils and cultivated soils developed on the terraces and river floodplains on both sides of the Brahmaputra River and its tributaries have better fertility and are the main areas for agricultural and livestock production [14–16].

Gyaca walnuts are characterized by their thin skin, full walnut kernels, and delicious taste. Walnut trees grow naturally without the use of any chemical fertilizers or pesticides. Their roots mainly absorb nutrients from fallen leaves and plant residues, which results in a nutrient supply that is not sufficient to meet the growth needs of walnut trees. Therefore, soil nutrients are crucial factors affecting walnut yield and quality in this region [17,18]. Du et al. [18] showed that microorganisms were strongly correlated with soil quality indices and significantly positively correlated with walnut yield. Xu et al. [19] found a highly significant positive correlation between walnut yields and AN and available potassium (AK) through correlation analysis. Furthermore, related studies have shown that there are significant differences in soil fertility between soils with different forest ages and parent materials, which affect the leaf nutrient content and photosynthetic product accumulation [20–23]. Therefore, this study aims to explore the soil fertility characteristics of walnut orchards with different parent materials and soil types in Gyaca County, Tibet. Five representative walnut orchards with different parent materials and soil types were selected for soil nutrient determination and leaf nutrient analysis. These findings aim to provide a reference for nutrient management and soil improvement in walnut orchards, enhancing the understanding of soil fertility evaluation in the main production areas of Tibetan walnuts. This effort is important for promoting the sustainable development of the walnut industry in the Tibetan Plateau.

2. Materials and Methods

2.1. Experimental Site

Gyaca County is located in the southeast of the Tibet Autonomous Region, in the middle reaches of the Brahmaputra River. It is under the jurisdiction of Shannan city, and urban and cultivated areas are mainly located in the valleys of the north and south banks of the Brahmaputra River and its slopes and tablelands. Gyaca County has a plateau-

temperate semi-arid monsoon climate, long sunshine hours (~7.5 h/24 h), an insufficient effective accumulated temperature, with an average annual temperature of 8.9 °C, and an average annual rainfall of 493 mm. The selected five walnut orchards are located at altitudes ranging from 3000 to 3500 m [11,24,25]. Gyaca County straddles the Gangdise mountain range, the Himalayan depression zone, and the Brahmaputra plate combination zone, has a complex geological environment and soil environment, and the soil parent materials consist of slate, gneiss, phyllite weathering development, and Quaternary loose deposits [24,25].

2.2. Experimental Design

The experiment was conducted in mid-July 2022, with soil and plant samples collected from five representative walnut orchards located in Anrao and Gyaca towns, the main walnut production areas in Gyaca County, Shannan city, Tibet. These five walnut orchards have different soil parent materials and soil types and are not affected by human factors such as chemical fertilization and pesticide spraying. Basic information about the sampling locations and soil properties in the walnut orchards is shown in Table 1, and the landscape and soil morphological characteristics of the orchards are shown in Figure 1. To minimize sampling errors, walnut trees of similar growth were selected from the five orchards for soil and leaf sample collection employing a multi-point sampling strategy. Six 40 cm-deep soil profiles were collected at 35 cm from the drip line of the walnut canopy. Soil samples from depths of 0–20 cm and 20–40 cm were collected and mixed using the quartering method. Four repeated samplings were carried out in each orchard, with a total of 20 soil samples collected. One kilogram of soil was then taken to the laboratory after removing plant residues, sand, and stones, dried, ground to pass through 0.85 mm and 0.15 mm sieves, and stored in sealed bags for soil nutrient determination. During the process of sampling the leaves of walnut trees, mature and stable leaf samples were collected from the middle part of the outer trunk in all four directions (east, south, west, and north) and then mixed [26]. Approximately 500 g of leaves were collected from each walnut tree, and a total of 20 walnut leaf samples were ultimately collected. After returning the leaves to the laboratory, the leaves were washed with distilled water, placed in an oven to kill the chlorophyll at 105 °C for 20 min, and then dried to a constant weight at 50 °C. Finally, the dried leaves were ground to pass through a 0.15 mm sieve and stored in sealed bags for leaf nutrient analysis.

Table 1. Basic information on sampling sites and soil properties.

Sampling Site		East Longitude (°)	North Latitude (°)	Altitude	Parent Material	Soil Type	Soil Texture	Lithology
Ciren village	Anrao Town	92.540528	29.145719	3112 m	sediment	Calcareous alluvial soil	Light sandy soil/sandy loam soil	Sedimentary rock
Sangzhu village	Anrao Town	92.535658	29.145639	3550 m	eluvium	Mountain meadow soil	Heavy sandy soil/sandy loam soil	Rock debris/mineral debris
Lagang village	Anrao Town	92.560950	29.154678	3364 m	deluvium	Plateau prairie soil	Heavy sandy soil/sandy loam soil	Clastic rock/clay rock
Reguo village	Anrao Town	92.582594	29.152833	3280 m	deluvium/ sediment	Gray-cinnamon soil	Heavy sandy soil/sandy loam soil	Rock debris/mineral debris/clastic rock/clay rock
Longba village	Gyaca Town	92.731169	29.080989	3248 m	glutenite	Brush prairie soil	Extremely heavy sandy soil/sandy loam soil	Sand/gravel



Figure 1. Sampling of walnut orchard landscape and soil morphology. The soil in the third row of images has been sieved through a 0.85 mm aperture sieve.

2.3. Sample Testing

Soil sample analysis: The soil pH, SOM, and TN were determined using a pH meter, the potassium dichromate external heating method, and the semi-micro Kjeldahl method, respectively. The AN, AP, AK, and SAK were determined using the alkaline diffusion method, molybdenum antimony anti-colorimetric method, and flame photometry, respectively [27–29]. The soil microbial biomass carbon (MBC), nitrogen (MBN), and phosphorus (MBP) were determined using the chloroform fumigation leaching method [30].

Plant sample (walnut leaves) analysis: Plant samples were digested with concentrated H_2SO_4-H_2O_2 to prepare the test solutions, which were then analyzed using the Kjeldahl method to determine the total nitrogen (PN) content, and the molybdenum antimony anti-colorimetric method to determine the total phosphorus (PP) content [31,32]. A flame photometer (FP640) was used to determine the total potassium (PK) content of the plant leaf samples [33].

2.4. Data Processing and Analysis

The experimental data were organized and calculated using MS Excel 2019. The correlation analysis of soil properties and plant nutrients were completed using Origin2021. Soil texture was classified according to the Chinese soil texture classification standard. The software used for redundancy analysis (RDA) was Canoco5.0. SPSS 18.0 was used for statistical analysis, and the Pearson method was used for correlation analysis. The LSD method was used to conduct post-hoc tests ($p < 0.05$). When $p < 0.05$, the result was considered significantly different, and when $p < 0.01$, the result was considered highly significantly different.

3. Results

3.1. Influence of the Parent Material and Soil Type on Walnut Orchard Soil Properties

The soil types in Gyaca have a characteristic mountainous vertical distribution, with the altitude showing a pattern of mountain meadow soil > plateau prairie soil > brush prairie soil > gray-cinnamon soil and calcareous alluvial soil. The results shown in Table 2 indicate that the soils in the five walnut orchards have weakly alkaline pH values, ranging from 7.06 to 7.61, with an average of 7.36. Significant differences were found among different soil types and soil layers. The organic matter content in walnut orchard soils developed from different parent materials and soil types in Gyaca County ranged from 16.5 to 51.4 g/kg, exhibiting significant differences between different soil layers. Specifically, the organic matter content in Lagang village and Sangzhu village soils was relatively low, with averages of 19.25 g/kg and 17.0 g/kg, respectively, which were notably lower than those in the soils of the other three walnut orchards. The average SOM and TN content of the soils in each orchard were 29.7 and 0.03 g/kg, respectively. Among them, the soil layers of 0–20 cm and 20–40 cm in Reguo village and Ciren village had the highest SOM and TN contents, with SOM contents of 51.4, 38.0, and 38.9, 39.3 g/kg, respectively, while the TN contents were 0.06, 0.02 and 0.06, 0.03 g/kg, respectively, varying greatly between soil layers. The average contents of soil AN, AP, AK, and SAK were 2.15, 8.52, 109.3, and 1315.8 mg/kg, respectively, indicating that the surface and subsoil soils of the plateau walnut orchards had a seriously low supply of nitrogen, while the phosphorus supply was medium and the potassium supply was the highest. Therefore, the combined soil results reflected that walnut orchards developed on gray-cinnamon soil derived from sediment and deluvium had the highest fertility level. The comprehensive representation of available nutrient levels in the soils was gray-cinnamon soil and calcareous alluvial soil > mountain meadow soil > plateau prairie soil and brush prairie soil.

Table 2. Soil chemical properties of walnut orchards in Gyaca County.

Sampling Site	Soil	pH	SOM (g/kg)	TN (g/kg)	AN (mg/kg)	AP (mg/kg)	AK (mg/kg)	SAK (mg/kg)
Ciren	0–20 cm	7.42 ab	38.9 b	0.06 a	3.99 a	21.73 a	194.8 a	1126.2 b
village	20–40 cm	7.06 c	39.3 b	0.03 b	2.85 b	10.14 b	82.4 b	1064.1 b
Sangzhu	0–20 cm	7.52 a	20.7 c	0.04 b	1.43 c	4.03 c	73.5 b	579.6 d
village	20–40 cm	7.61 a	17.8 d	0.02 c	1.03 c	5.41 c	55.3 c	535.4 d
Lagang	0–20 cm	7.51 a	16.5 c	0.02 c	0.86 d	3.31 c	57.4 c	2539.7 a
village	20–40 cm	7.33 b	17.4 d	0.03 b	0.61 d	2.25 c	47.1 c	2519.3 a
Reguo	0–20 cm	7.18 c	51.4 a	0.06 a	4.15 a	23.10 a	273.5 a	1476.5 b
village	20–30 cm	7.41 ab	38.0 b	0.02 c	3.53 ab	13.11 b	229.2 a	1768.4 b
Longba	0–20 cm	7.36 bc	32.8 b	0.05 a	2.13 b	1.91 c	50.8 c	780.9 c
village	20–40 cm	7.25 c	23.9 c	0.03 b	0.92 c	0.18 d	29.2 d	767.6 c
Average		7.36	29.7	0.03	2.15	8.52	109.3	1315.8

Note: Different lowercase letters for the same item indicate significant differences at $p < 0.05$. SOM, TN, AN, AP, AK, and SAK denote soil organic matter, total nitrogen, available nitrogen, available phosphorus, available potassium, and slowly available potassium, respectively.

3.2. Influence of Parent Material and Soil Type on Microbial Nutrition in Walnut Orchards

The transformation of carbon, nitrogen, and phosphorus in plateau soils mainly occurs with the participation of microorganisms, hence, the contents of MBC, MBN, and MBP are important parameters reflecting microbial activity. As shown in Figure 2, the average contents of MBC, MBN, and MBP in the different soil layers of the five walnut orchards were 368.8, 28.4, and 23.6 mg/kg, respectively. Overall, the trend was MBC > MBN > MBP and the content in the 0–20 cm layer was higher than that in the 20–40 cm layer. The MBC content in the 0–20 cm soil layer of the Longba village walnut orchard was the highest, reaching 579.1 mg/kg. The MBN content in the 20–40 cm soil layer of Reguo village walnut orchard was the highest, reaching 61.0 mg/kg, and the MBP content in the 0–20 cm soil layer of Ciren village was the highest, reaching 55.9 mg/kg. These findings indicated that

there were significant differences in microbial activity among soils with different parent materials and types.

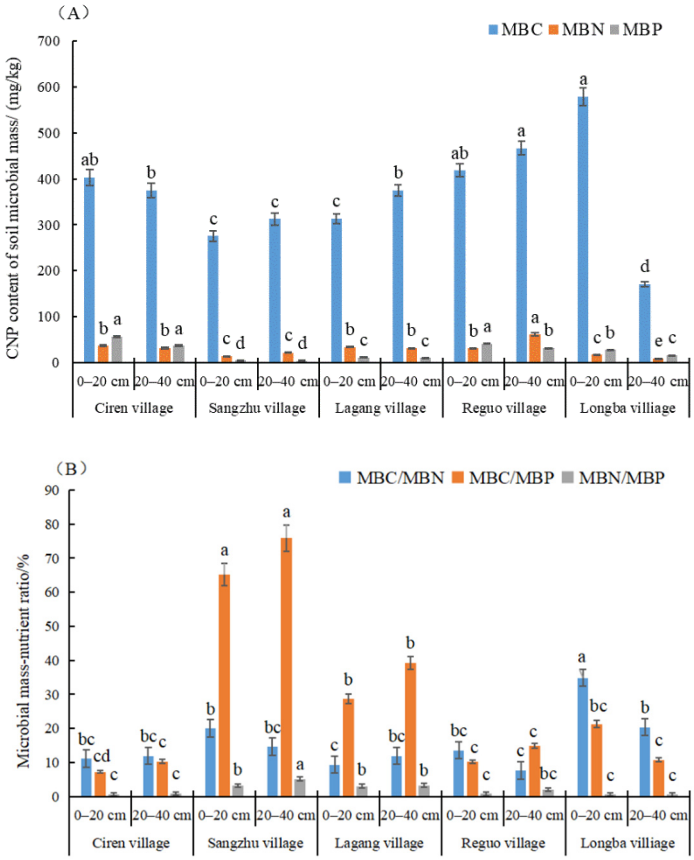


Figure 2. Effect of parent material and soil type on walnut orchard soil microbe activity. (**A**): The contents of MBC, MBN, and MBP in different soil layers of five walnut orchards. (**B**): The microbial biomass ratios in different soil layers of five walnut orchards. MBC, MBN, and MBP denote microbial biomass carbon, microbial biomass nitrogen, and microbial biomass phosphorus, respectively. Different lowercase letters for the same item indicate significant differences at $p < 0.05$.

3.3. Influence of Parent Material and Soil Type on the Nutrient Content in Walnut Leaves

Leaf nutrient status is an important indicator of nutrient diagnosis in fruit trees. From the results shown in Figure 3, it could be seen that the soils developed from different parent materials had a significant impact on the PN, PP, and PK contents of walnut leaves. The N, P, and K contents of walnut leaves in each orchard ranged from 0.49–0.88%, 0.16–0.35%, and 0.59–1.48%, respectively, with averages of 0.73%, 0.21%, and 1.03%, respectively, manifested as K > N > P. Specifically, Ciren village had the highest N and P contents in walnut leaves at 0.88% and 0.35%, respectively, while Lagang village had the lowest N and P contents at 0.49% and 0.16%, respectively. The K content of walnut leaves was highest in Sangzhu village and Lagang village, with 1.42% and 1.48%, respectively, while Longba village had the lowest K content at only 0.59%. The leaf nutrient status indicated that soils that developed from alluvial parent materials (calcareous alluvial soil) were favorable for N and P accumulation in walnut leaves, while mountain meadow soil and plateau prairie soil were favorable for K accumulation, but the N and P contents were relatively low.

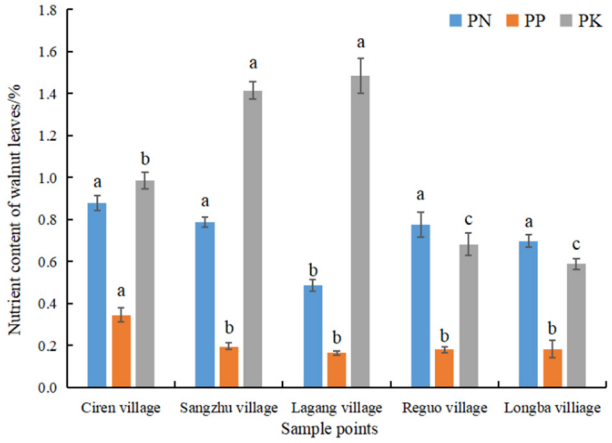


Figure 3. Effects of soil parent material and soil type on walnut orchard leaf nutrients. PN, PP, and PK denote plant nitrogen, plant phosphorus, and plant potassium, respectively. Different lowercase letters for the same item indicate significant differences at $p < 0.05$.

3.4. Inter-Relationships between Soil Nutrients and Plant Nutrients

There were varying degrees of correlation between walnut leaf nutrients, including PN, PP, and PK, and soil nutrients (Figure 4). Nitrogen and phosphorus nutrition showed a mutual assistance relationship. The PN content had a significant positive correlation with SOM and MBP contents ($p < 0.05$), and a highly significant positive correlation with PP content, TN, and AN ($p < 0.01$), while it had a highly significant negative correlation with SAK ($p < 0.01$). The PP content had a significant positive correlation with MBP content ($p < 0.05$), while its correlations with other indicators were not significant. The PK content had a highly significant positive correlation with pH ($p < 0.01$) and highly significant negative correlations with SOM, TN, AN, MBC, and MBP ($p < 0.05$), with no significant difference observed between other indicators.

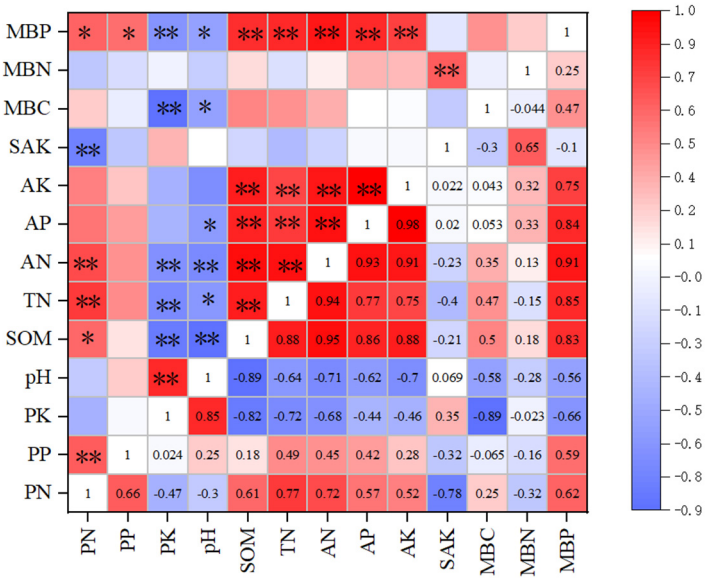


Figure 4. Correlation analysis of soil properties and plant nutrients. Note: * and ** indicate significant differences at the $p < 0.05$ and $p < 0.01$ levels, respectively.

According to the redundancy analysis (RDA), the influences of various soil nutrient indicators on the nitrogen, phosphorus, and potassium contents of plant leaves are shown in Figure 5. The results showed that the contribution rates of soil properties and microbial activity indicators to the nitrogen, phosphorus, and potassium contents of plant leaves added up to 93.5%, among which the explanation rates of ordination axis 1 and ordination

axis 2 were 77.4% and 16.1%, respectively. The five indicators of TN, AN, SOM, MBC, and SAK in the soil had the greatest impact on leaf nutrient levels. Plant leaf nitrogen nutrition and phosphorus nutrition had a clear positive effect, while the interaction with potassium nutrition was not significant.

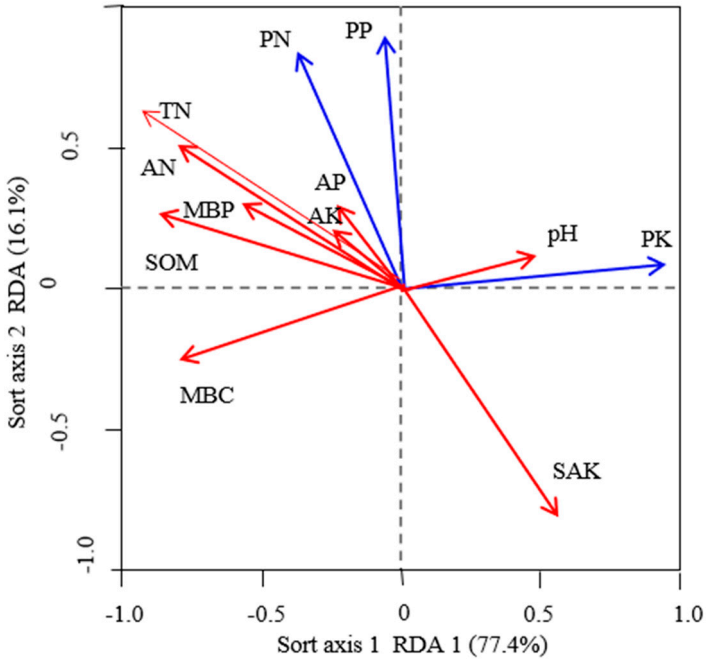


Figure 5. Redundancy analysis of soil properties and plant nutrients.

4. Discussion

The characteristics of soil fertility are closely related to soil parent material and soil type, which affect the absorption capacity of walnut trees for soil nutrients [20]. The mineral composition of the soil is greatly influenced by the parent material, and there are significant differences in nutrient content among soils developed from different parent materials, with soil pH and organic matter content providing important indicators of soil properties [22,34]. The soil pH in the five representative walnut orchards in Gyaca County was >7.0 (Table 2), indicating a weakly alkaline level and no potential risk of acidification, making it very suitable for the growth and development of plateau walnuts. Organic matter content influences soil physical and chemical properties, plays important roles in walnut yield, quality, and soil fertility, and provides an important source of the essential elements required by walnuts [35,36]. The organic matter contents in Lagang village and Sangzhu village soils were relatively low, significantly lower than those in the soils of the other three walnut orchards (Table 1). The walnut orchard in Lagang village is the oldest, being approximately 1000 years old, with a soil type of plateau prairie soil developed from deluvium. Due to the long natural formation time of the walnut orchard, the rates of soil nutrient depletion and organic matter mineralization were higher than the rate of organic matter accumulation, thus decreasing the SOM content. However, Sangzhu village is a newly established walnut orchard on a wasteland covered with grass, with a soil type of mountain meadow soil. Among the five walnut orchards, Sangzhu village is located at the highest altitude of 3550 m. Therefore, its nutrient content and organic matter accumulation are insufficient. Ciren village and Reguo village are located in the river valley zone, with soils developed from sediment and the most diverse crop types, including walnut, winter wheat, barley, and winter oilseed. These soils had the highest organic matter and nutrient content, as well as the highest crop yield level, making them the main agricultural production areas in Gyaca County [11]. Longba village is developed from gravel sandstone and has a brush prairie soil. From the results in Table 2, significant

differences could be seen in the organic matter content between the 0–20 cm and 20–40 cm soil layers, which were due to the significant human factors influencing the walnut orchard in Longba village. The surface gravel has been removed and a large amount of organic fertilizer has been applied to improve the soil, resulting in a much higher organic matter content in the surface soil than in the subsoil.

Soil available nutrients have a certain degree of inheritance from the parent material, causing the content of available nutrients to vary among soils developed from different parent materials. The influence of soil types and lithology on nutrient availability cannot be overlooked. Sandy soils tend to have lower nutrient retention capacity, while loam soils are more fertile due to their higher nutrient-holding capacity. Furthermore, lithology, or the parent rock from which the soil was derived, can also affect nutrient availability, as some rocks are more nutrient-rich than others [37–39]. In the present study, investigating the soil available nutrient content showed that the soil TN and AN contents in the five walnut orchards were relatively low (Table 2). Zhang et al. [5] evaluated soil fertility in Xinjiang walnut orchards and found that the long-term cultivation of walnut trees requires reasonable fertilization to supplement SOM, AN, AP, and AK contents, as well as trace elements such as calcium, magnesium, and zinc. Zhao et al. [26] evaluated soil fertility in the main walnut-producing areas of Shanxi province and found that walnut orchard nutrition was at a medium to low level, with AP, SOM, and AN contributing the most to yield. Therefore, nitrogen nutrition limitation is also a major factor in the relatively low level of walnut production in the Tibetan Plateau, and there is a significant difference in AN levels between this region and walnut orchards in the Xinjiang and Yunnan–Guizhou regions. The levels of AP and AK in walnut orchards developed from different parent materials were relatively moderate to low, although the level of SAK was higher than the others. However, the sustainability of the potassium and phosphorus supply in walnut orchards in this region is still unknown. In addition, the results of soil microbial activity analysis (Figure 2) showed that compared to the low levels of soil available nutrients and walnut leaf nutrient content, there was a significant accumulation of microbial carbon, nitrogen, and phosphorus content, especially in the walnut orchards of Sangzhu village, Lagang village, and Longba village, and the soil fertility was lower than that of Ciren village and Reguo village, leading to a significant increase in microbial nitrogen content and the C/P ratio, which increased with soil depth. It can be seen that the absorption of nutrients by soil microorganisms in plateau walnut orchards mainly supplies their own growth and reproduction and competes with walnut roots for available nutrients [40,41].

Plateau walnuts are perennial trees that grow in a fixed soil environment for a long time and have a high demand for soil mineral nutrients [42]. The results of this study show the significant differences in the growth of walnut plants in soils developed from different parent materials and types, especially in the walnut orchards of Sangzhu village and Longba village, which are newly established plantations with low levels of soil available nutrients. Therefore, it is necessary to improve soil fertility and increase the soil nutrient supply, especially nitrogen, through appropriate fertilization. The mineral nutrition status of leaves can reflect the physiological status of trees and the nutrient status of the soil to some extent [33]. The results shown in Figure 4 revealed correlations between nitrogen, phosphorus, and potassium nutrition in walnut leaves with soil nutrients to varying degrees, and showed that nitrogen and phosphorus nutrition had a mutually beneficial relationship. The redundancy analysis (Figure 5) also confirmed that the environmental factors contributed to leaf nutrition at a rate of 93.5%. In contrast to their counterparts in the Xinjiang and Yunnan–Guizhou Plateau regions, plateau walnut farmers in Tibet mainly practice ecological planting without the use of chemical fertilizers and pesticides. They primarily rely on scattered cow manure, which is limited in quantity and cannot meet high yield requirements. Li et al. [43] found that arbuscular mycorrhizal fungi could enhance the absorption and utilization of water and mineral nutrients in Yunnan plateau walnuts and enhance the adaptability of walnut trees to biotic and abiotic stress. Therefore, to increase the yield and quality of plateau walnuts in Tibet, walnut orchards in the five producing

areas can apply plant-derived protein waste, humic acid organic fertilizers, biogas slurry, and well-fermented livestock manure supplemented with microbial inoculants [44]. This approach is beneficial for protecting the environment and can increase the soil available nutrient content and improve the fertility level of walnut orchards.

5. Conclusions

In the main production area of Gyaca County in Tibet, the soil pH of walnut orchards was above 7.0, indicating a weakly alkaline environment suitable for the growth and development of plateau walnuts. Soils developed from different parent materials and types showed significant differences in SOM, TN, available nutrient content, and microbial activity. Among them, walnut orchards developed on gray-cinnamon soil derived from sediment and deluvium had the highest fertility level, followed by calcareous alluvial soil, mountain meadow soil, plateau prairie soil, and brush prairie soil. The level of nitrogen supply in the soil was found to be the first limiting factor for leaf nutrition and yield formation in existing plateau walnut orchards in Tibet. Therefore, the application of organic nitrogen fertilizers should be emphasized to improve soil fertility and maintain or increase walnut yield and quality. When selecting new land for walnut orchards, it is important to consider the soil formation conditions and the supply capacity of available nutrients.

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Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare that they have no conflicts of interest.

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