

Article

Analysis of Soil Nutrient and Yield Differences in Korla Fragrant Pear Orchards Between the Core and Expansion Areas

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Abstract

Soil samples of different tree ages from the core area and expansion area of Korla City were selected to determine their nutrients and yield, and the analysis was combined with a Principal Component Analysis (PCA) biplot. The soil fertility and yield in the core area were superior to those in the expansion area. PCA biplot analysis showed that the cumulative variance contribution rate of the principal components of the orchard with a tree age of 10–20 years was 80.60%. PC1 had strong positive loadings for calcium, available phosphorus, organic matter, total nitrogen, and yield, and a strong negative loading for pH. PC2 had strong loadings for manganese, zinc, copper, selenium, and iron, as well as for magnesium, boron, available nitrogen, and electrical conductivity. For the core area, soil conditions need to be maintained. For the expansion area, salinization should be addressed; the input of Mg and B should be controlled; and the application of calcium, phosphorus fertilizers, and organic fertilizers should be increased to improve production and quality.

Keywords: Korla fragrant pear; soil nutrients; yield; principal component



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1. Introduction

The Korla fragrant pear (*Pyrus sinkiangensis* Yu) is a unique pear tree variety in Xinjiang Uygur Autonomous Region, China [1]. In Korla City, Xinjiang Uygur Autonomous Region, and its surrounding areas, such as Luntai County, Yuli County, Aksu City, and Awati County, a special pear variety is grown with a cultivation history of over 1400 years: the Korla fragrant pear. It belongs to the White Pear series of the genus *Pyrus* in the Rosaceae family and represents a natural hybridization of Hanhai pear (*Pyrus himalaica*) and Ya pear (*Pyrus bretschneideri* Rehd) [2]. Korla fragrant pears are characterized by rich flavor, thin skin without residue, crisp texture, juiciness, and abundant nutrients [3]. Notably, their high vitamin C and mineral content provide benefits such as lung moistening, cough relief, and phlegm elimination [4], earning them the reputation of “natural mineral water” among fruits [5].

In recent years, with the continuous expansion of cultivation areas, problems like tree aging and declining fruit quality have become public concerns. These issues significantly reduce economic benefits and consumer satisfaction while constraining the sustainable development of the fragrant pear industry [6]. As living standards improve, consumer demand for premium fruits increases daily, and global demand for Korla fragrant pear

continues to rise annually [7]. To meet this growing market demand, cultivation areas have expanded progressively, forming a coordinated spatial pattern with the traditional core region as its center and a peripheral expansion area. The core production area resides within Awati County under Korla City's jurisdiction. For agricultural development promotions, Yingxia County has been designated as an important expansion cultivation area for Korla fragrant pears [8]. Soil nutrients, as a key ecological element affecting the growth, development, and fruit quality of fruit trees, have a significant impact on yield [9]. Sun et al. [10] found that the growth, fruit yield, and quality of pear trees in different cultivation areas are greatly affected by soil conditions and the nutrient status of the trees. However, at present, there is a lack of in-depth comparisons of the systematic differences in soil nutrients in Korla pear orchards, especially in the content characteristics of macronutrients and micronutrients, the balance relationship of elements, and the regional differentiation of physical and chemical properties such as soil salinization (electrical conductivity). The research on the correlation mechanism between soil nutrient indicators and the yield of fragrant pears is insufficient, and it has not been clear which specific nutrients (or imbalance characteristics) are the core driving factors leading to regional yield differences. The direction of soil improvement for the low yield problem in the expansion area lacks scientific basis and struggles to support the demands of precise planting and management. These factors prevent the fragrant pear industry from achieving targeted regulation of soil nutrients during regional expansion, which restricts the stable improvement of yield and quality.

Based on the above analysis, we propose the following hypothesis: The significant yield gap between the core area and the expansion area is mainly driven by the soil nutrient status; therefore, soil nutrients are positively correlated with the yield of Korla fragrant pears. The soil nutrient characteristics in different regions are the main factors leading to yield differences. Therefore, in view of the current practical problems in Xinjiang's characteristic forestry and fruit industry, such as significant yield differences between the core area and the expanded area of Korla fragrant pears, unclear regional differentiation characteristics of soil nutrients, and the lack of scientific basis for precise fertilization and soil improvement measures, this study focuses on two core goals: First, by analyzing the variation patterns of soil nutrients in the core area and the expansion area, the quantitative correlation between soil nutrients and yield and the key driving factors of regional yield differences are clarified. The second is to propose targeted soil management strategies based on regional characteristics. Through the above research, not only can theoretical support be provided for the optimization of precise fertilization in the core area, the improvement of soil salinization in the expansion area and regionalized soil management, but also the lack of targeted research on the regional nutrient-driven mechanism of characteristic forest fruits can be addressed. This has important practical significance for promoting the quality improvement, efficiency increase and sustainable development of Xinjiang's characteristic forest fruit industry.

2. Materials and Methods

2.1. Study Site

The data of cultivated land use in Korla City, Xinjiang Uygur Autonomous Region, before 2000 and from 2000 to 2020 were analyzed. Before 2000, the land use policy was relatively loose. With its superior natural conditions and irrigation resources, Awati County was developed on a large scale to form a core cultivation area. After 2000, with the adjustment of land use policies and the advancement of urbanization, Yingxia County, due to its great potential for land development and better adaptability to the new demands of agricultural development, became the principal area for additional cultivated land,

designated as the expansion area. The newly added cultivated land area before 2000 is the core cultivation area (referred to as the core area), located in Awati County, Korla City, at an altitude of 890–920 m. The mother orchards of fragrant pears were established in 1958, and there are still rich resources of ancient trees that are over 50 years old. The soil is irrigated and silted soil, with the core area being loam. It mainly has a granular structure and is primarily composed of organic fertilizer and compound fertilizer. The organic matter content in the plough layer (0–20 cm) is high. It relies on gravity-flow irrigation of snowmelt runoff from the Tianshan Mountains. The climate belongs to a temperate continental climate, with cold and dry winters and hot and windy summers. The total sunshine duration is approximately 2990 h, the average frost-free period is about 210 days, and the annual average temperature is 11.4 °C.

From 2000 to 2020, the newly added cultivated land area was designated as the expansion cultivation area (referred to as the expansion area), located in Yingxia County, Korla City. The altitude ranges from 870 to 880 m. After 2000, the proportion of newly added cultivated land is high. The soil is mainly salinized irrigation and siltation soil with block structure. The expansion area is sandy loam soil, and soil salinization is severe. The expansion area mainly uses compound fertilizers, with less application of organic fertilizers and low organic matter content. The groundwater is buried 4–6 m deep and relies on wells for irrigation. The frost period is 7–10 days earlier than that in the core area, and the climate belongs to the temperate continental climate. The winter is cold and dry, while the summer is hot and windy. The total duration of sunshine reached approximately 3000 h, the average frost-free period was about 215 days, and the annual average temperature remained at around 11.5 °C.

2.2. Experimental Design

This study adopted a two-factor experimental design of “region × tree age”, in which the region was divided into the core area (Awati County) and the expansion area (Yingxia County). Based on the distinct stage development characteristics of different ages in the growth cycle of fragrant pears, they are divided into three gradients according to the cultivation years, corresponding, respectively, to the key development stages of fragrant pears: From 0 to 5 years, plants are in the young stage, mainly exhibiting growing vegetative, with weak adaptability to the environment, and are prone to nutrient deficiency, resulting in growth retardation. From 5 to 10 years, it is the initial production period, during which fruits gradually transition from vegetative growth to reproductive growth, and it is expected that soil nutrient content and fruit yield will increase. From 10 to 20 years, it is the peak production period, during which fruits grow and mature, and reproductive growth capacity reaches its peak. Preliminary investigations in the early stage show that the growth status, field management measures, and annual yield of plants within the same tree age gradient are relatively small. This not only indicates that the cultivation and management levels of orchards within the same gradient are consistent, but also verifies that fragrant pears at the same developmental stage conform to the inherent physiological and production expectations of that age, and there are significant differences among different tree age gradients. Therefore, three representative orchards were selected, respectively, under each tree age gradient in each area as biological replicates, and five soil samples were collected from each orchard. The specific sampling distribution is shown in Figure 1.

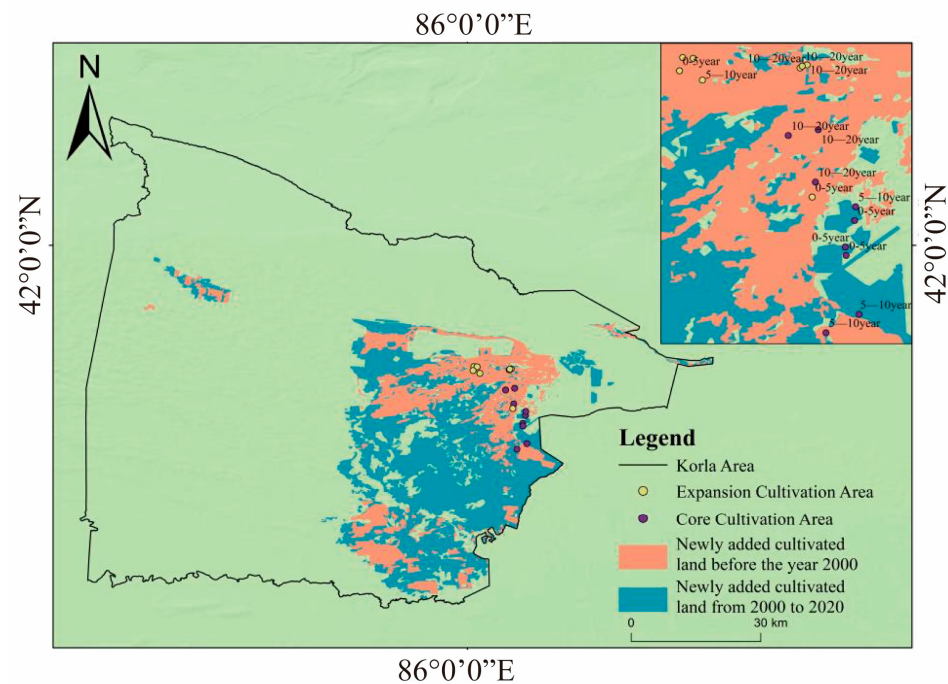


Figure 1. Distribution map of sample collection of Korla fragrant pear.

2.3. Collection and Determination of Samples

2.3.1. Sample Collection

Before the harvest of fragrant pears on 6 September 2024, the yield was measured first. From each fragrant pear tree, 10 fragrant pears with good growth and development were randomly picked from top to bottom in the four directions of east, south, west, and north. The rootstock for the grafting of fragrant pears was *Pyrus betulifolia*. They were transported back to the laboratory for determination of single-fruit weight. Based on the area of the orchard and the uniformity of the soil, a checkerboard layout was adopted, avoiding special locations such as the edges of fields and ditches. After removing the fallen debris on the surface, soil drill samples (0–20 cm) were taken within the canopy width of the fragrant pear trees. Five sample points were collected from each orchard and mixed to form one sample to be tested. The soil samples were stored in self-sealing bags and taken back to the laboratory for air drying, impurity removal, grinding, sieving, mixing, bottling for storage and registration, etc., for the purpose of analysis and testing. The total nitrogen, organic matter, alkali-hydrolyzable nitrogen, available phosphorus, available potassium, pH, electrical conductivity, and elements were determined.

2.3.2. Measurement and Calculation

Measurement methods are detailed as follows: Table 1 presents the soil nutrient classification criteria for Xinjiang [11,12], while Table 2 outlines the yield grading standards for Korla fragrant pear [13]. Soil physicochemical parameters were determined following the methodologies described in Bao Shidan's Soil and Agricultural Chemistry Analysis: The pH was measured using a pH meter at a soil-to-water ratio of 2.5:1. EC was assessed with a conductivity meter. TN and SOM were quantified using the semi-micro Kjeldahl method and potassium dichromate external heating method, respectively. AN was determined via alkaline hydrolysis diffusion, AP through sodium bicarbonate extraction-molybdenum antimony anti-colorimetric analysis, and AK via ammonium acetate extraction-flame photometry. Elemental composition was analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES) and inductively coupled plasma mass spectrometry (ICP-MS) [14].

Table 1. Soil nutrient classification standards.

Nutrient Name	Grading Standard					
	Rich		Flat		Lack	
	1	2	3	4	5	6
SOM (g·kg ^{−1})	≥40	30–40	20–30	10–20	6–10	<6
TN (g·kg ^{−1})	≥2.0	1.5–2.0	1.0–1.5	0.5–1.0	0.3–0.5	<0.3
AN (mg·kg ^{−1})	≥150	120–150	90–120	60–90	30–60	<30
AP (mg·kg ^{−1})	≥40	20–40	10–20	5–10	3–5	<3
AK (mg·kg ^{−1})	≥200	150–200	100–150	50–100	30–50	<30
pH	≥8.5	8.0–8.5	7.5–8.0	7.0–7.5	6.5–7.0	<6.5
EC (dS/m)	≥4.0	3.0–4.0	2.0–3.0	1.0–2.0	0.5–1.0	<0.5

Table 2. Classification standards for the output grades of Korla fragrant pear.

Tree Age/(years)	High-Yield Orchard/(kg·hm ²)	Low-Yield Orchard/(kg·hm ²)
0–5	≥15,000	<7500
5–10	≥18,000	<9000
10–20	≥27,000	<12,000

2.4. Statistical Analyses

In this study, all experiments were independently repeated three times (three sample plots were collected from the same area and the same tree age), and results are presented as the mean ± standard deviation ($n = 3$) to ensure the reliability and repeatability of the data. Soil nutrient data and Korla fragrant pear yield records were organized using WPS Office 2021. Statistical analyses were performed using Statistix 9.0 software (Tallahassee, FL, USA), with data subjected to a one-way analysis of variance (ANOVA) under a completely randomized design. Tukey’s honestly significant difference (HSD) test was applied for post hoc multiple comparisons at a significance level of $p = 0.05$. Graphical illustrations were generated using Origin 2025 software (provided by OriginLab Corp.), while sampling location maps were created using ArcGIS 10.8 software.

3. Results

3.1. Soil Nutrient Characteristics of Korla Fragrant Pear in Different Regions

3.1.1. Characteristics of Soil Organic Matter and Total Nitrogen in Korla Fragrant Pear Orchards of Different Cultivation Areas and Tree Ages

According to Figure 2A, in the core area, the SOM content of trees aged 10–20 years is significantly higher than that of trees aged 10–20 years in the expansion area ($p \leq 0.05$), and the SOM content of trees aged 10–20 years in the core area is at the level of grade 2 in Table 1, indicating a relatively high soil fertility. There were also significant differences in SOM content among different tree age groups in the core area ($p \leq 0.05$). The SOM content of trees aged 10–20 years was significantly higher than that of trees aged 0–5 years ($p \leq 0.05$), indicating that with the increase in tree age, SOM in the core area gradually accumulated. In the expansion area, there were also significant differences in SOM content among different tree age groups ($p \leq 0.05$), but the overall content was lower than that in the core area. According to Figure 2B, the TN content in the soil of trees aged 10 to 20 years in the core area was significantly higher than that of trees aged 10–20 years in the expansion area ($p \leq 0.05$), and there were also significant differences in the TN content in the soil of different tree age segments in the core area ($p \leq 0.05$). The TN content of trees aged 10–20 years was significantly higher than that of trees aged 0–5 years and 5–10 years ($p \leq 0.05$), indicating that with the increase in tree age, the TN in the core area soil gradually accumulates. There

were also significant differences in the TN content of soil among different tree age groups ($p \leq 0.05$). According to Table 1, the TN content of soil in the core area was mostly at grade 2, while that in the expansion area was mostly at grade 4, indicating that the TN content of soil in the core area was significantly better than that in the expansion area overall ($p \leq 0.05$). Moreover, the organic matter and TN content of trees aged 10–20 years in the core area were significantly higher than those of trees of other ages ($p \leq 0.05$), providing a more fertile and healthy growth environment for fragrant pear trees, which is conducive to increasing the yield and quality of fragrant pears.

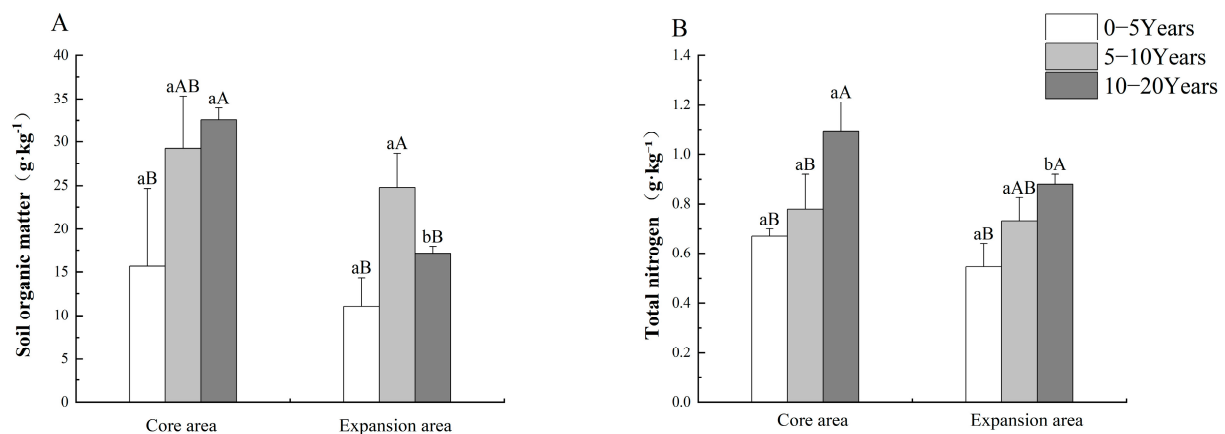


Figure 2. The soil content of Korla fragrant pear varies with different cultivation areas and tree ages: (A) Soil organic matter; (B) total nitrogen content. Note: Lowercase letters indicate significant differences in tree age within different areas ($p \leq 0.05$), while uppercase letters indicate significant differences in tree age within the same area ($p \leq 0.05$).

3.1.2. Characteristics of Available Nutrients in Korla Fragrant Pear Orchards of Different Cultivation Areas and Tree Ages

As shown in Figure 3A, the AN content in the core area for 0–5-year-old trees was significantly higher than that of the expansion area for 0–5-year-old trees ($p \leq 0.05$). According to the soil physicochemical property classification criteria in Table 1, the 0–5-year-old trees in the core area exhibited AN content at grade 5, while the expansion area's 0–5-year-old trees fell within grade 6. This indicates that the core area's soil provided more abundant nitrogen nutrition for Korla fragrant pear trees during early growth stages. The core area's trees aged 5–10 years and 10–20 years also showed higher AN content than those of the expansion area, though the differences were not statistically significant. As shown in Figure 3B, the soil AP content in the core area for 10–20 years of tree age was significantly higher than that in the expansion area for 10–20 years of tree age ($p \leq 0.05$). According to Table 1, the AP content in the core area was at the abundant level, while that in the expansion area was at the flat level. As shown in Figure 3C, the content of AK in the soil of the core area was not significantly different from that of the expansion area. According to Table 1, the AK content of trees aged 0–5 years and 5–10 years in the core area is at the same level, and that of trees aged 10–20 years reaches the abundant level, while, in the expansion area, all tree age segments are at the abundant level of grade 2, demonstrating the continuous advantage of phosphorus supply for the soil in the core area. Moreover, the AK in the core area for trees aged 10–20 years was significantly higher than that for other tree ages ($p \leq 0.05$), indicating that the content of available nutrients in the soil of the core area was superior to that in the expansion area in terms of key growth stages and important nutrient elements. This suggests that the nutrient supply capacity of the soil in the core area is stronger, which is more conducive to the growth and development of pear trees.

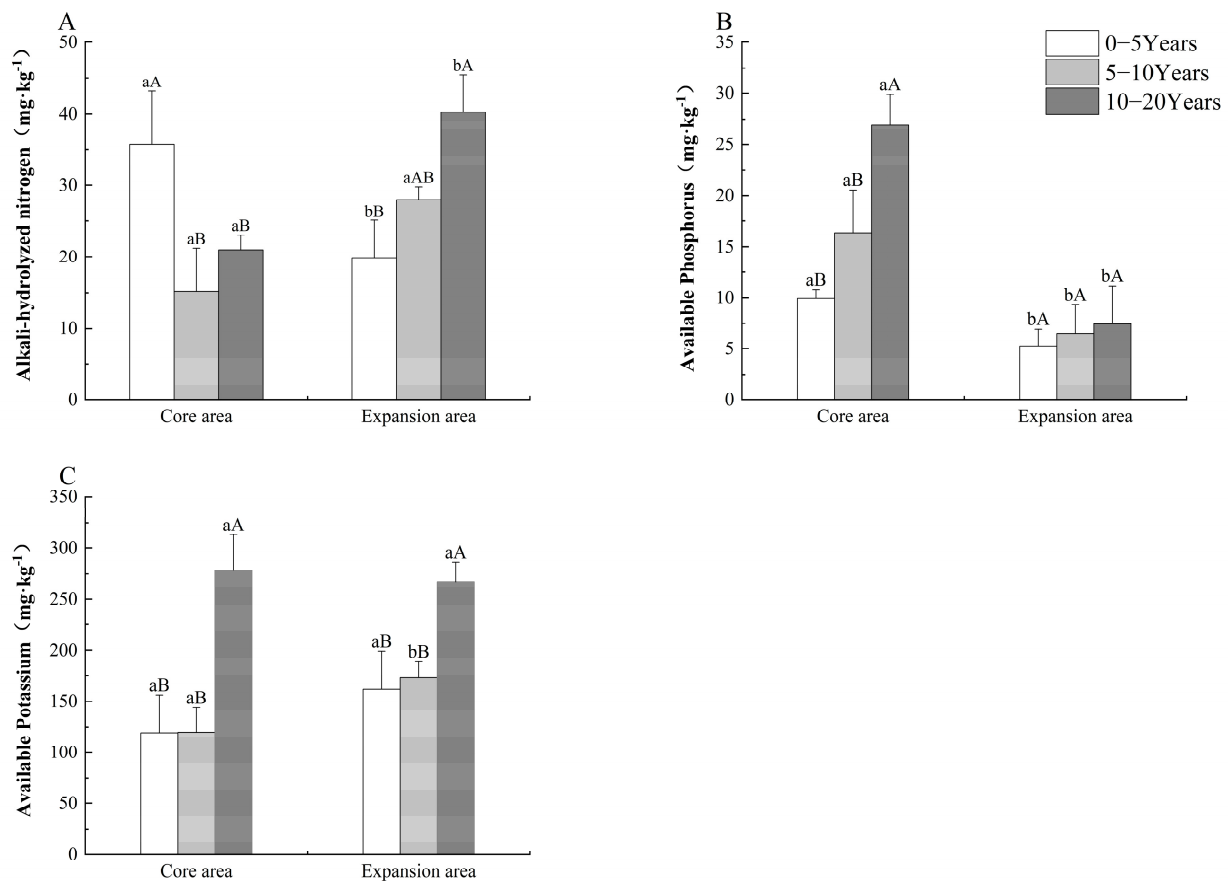


Figure 3. Available nutrients in Korla pear orchards of different cultivation areas and tree ages: (A) alkali-hydrolyzed nitrogen, (B) available phosphorus, (C) available potassium. Note: Lowercase letters indicate significant differences in tree age within different areas ($p \leq 0.05$), while uppercase letters indicate significant differences in tree age within the same area ($p \leq 0.05$).

3.1.3. Characteristics of pH and Electrical Conductivity in Korla Fragrant Pear Orchards of Different Cultivation Areas and Tree Ages

As shown in Figure 4A, the soil pH of trees of different ages in the core area and the expansion area remained stable at approximately 8. According to the soil physical and chemical property classification standards in Table 1, the pH levels of trees of different ages in the core area and the expansion area all belong to grade 3 (7.5–8.5), indicating that the soil's pH is relatively moderate, which is conducive to the availability of nutrients in the soil and the absorption and utilization by plants. The pH differences among trees of different ages in the core area and the expansion area were not significant, indicating that the pH in different regions and tree age segments was stable, and the pH in the core area was slightly better than that in the expansion area. As can be seen from Figure 4B, the EC of trees aged 0–5 years, 5–10 years, and 10–20 years in the core area shows significant differences ($p \leq 0.05$). The EC of trees aged 5–10 years in the expansion area was significantly ($p \leq 0.05$) higher than that of trees aged 0–5 years and 10–20 years. Moreover, the soil EC of trees of different ages in the core area was significantly lower than that in the expansion area ($p \leq 0.05$), indicating that the soil salinity status in the core area was better than that in the expansion area. This further indicates that the soil conditions in the core area are more suitable for plant growth. Moreover, compared with the expansion area, the soil salt accumulation in the core area is less, and the soil quality is better.

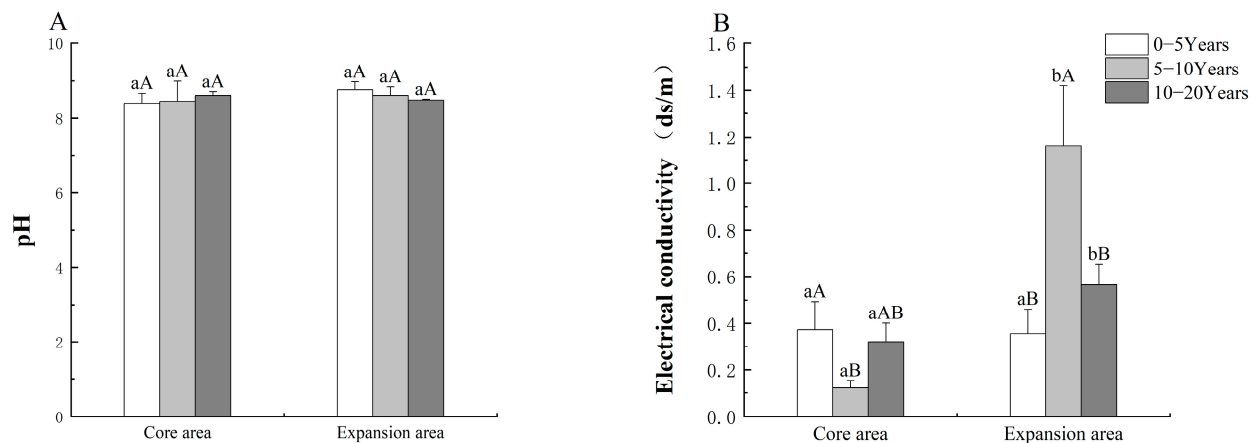


Figure 4. In Korla pear orchards, different cultivation areas and tree ages: (A) pH; (B) electrical conductivity. Note: Lowercase letters indicate significant differences in tree age within different areas ($p \leq 0.05$), while uppercase letters indicate significant differences in tree age within the same area ($p \leq 0.05$).

3.1.4. Characteristics of Trace Elements in the Soil of Korla Fragrant Pear of Different Cultivation Areas and Tree Ages

As shown in Table 3, in the core area, there were significant differences in the contents of Ca, Fe, Mg among trees of different ages ($p \leq 0.05$), while the contents of Zn, Mn, Cu, B, Se were not significantly different. Among them, the content of Ca showed an upward trend with the increase in tree age, increasing from 83.96 mg/g in 0–5 years to 115.81 mg/g in 10–20 years. The content of Fe was the highest in 0–5 years, at 34.05 mg/g, and decreased with the increase in tree age. The content of Mg reached its peak at 31.54 mg/g within 10–20 years. In the expansion area, there was a significant difference in the content of Ca among trees of different ages ($p \leq 0.05$), while the contents of Fe, Mg, Zn, Mn, Cu, B, Se did not show significant differences. The content of Ca gradually increased from 98.91 mg/g in 0–5 years to 107.84 mg/g in 10–20 years.

Table 3. Soil elements of Korla fragrant pear in different cultivation areas.

Soil Elements/ Different Regions	Core Area			Expansion Area		
	0–5 Years	5–10 Years	10–20 Years	0–5 Years	5–10 Years	10–20 Years
Ca (mg/g)	83.96 ± 14.66 aB	98.27 ± 6.89 aAB	115.81 ± 9.08 aA	98.91 ± 3.48 aB	105.18 ± 2.81 aAB	107.84 ± 1.73 aA
Fe (mg/g)	34.05 ± 3.93 aA	21.28 ± 2.50 aB	25.92 ± 1.54 aB	24.61 ± 3.34 bA	24.61 ± 1.01 aA	24.38 ± 1.59 aA
Mg (mg/g)	22.59 ± 0.52 bB	19.63 ± 2.41 bB	31.54 ± 0.53 bA	44.72 ± 1.38 aA	42.26 ± 5.69 aA	45.40 ± 3.40 aA
Zn (mg/g)	0.09 ± 0.02 aA	0.06 ± 0.01 bA	0.08 ± 0.01 aA	0.07 ± 0.01 aA	0.07 ± 0.004 aA	0.09 ± 0.01 aA
Mn (μg/g)	0.67 ± 0.05 aA	0.55 ± 0.18 aA	0.7 ± 0.08 aA	0.57 ± 0.09 aA	0.58 ± 0.06 aA	0.78 ± 0.20 aA
Cu (μg/g)	17.57 ± 2.05 aA	16.40 ± 1.83 aA	18.59 ± 0.36 aA	14.86 ± 3.47 aA	15.56 ± 0.35 aA	18.49 ± 3.28 aA
B (μg/g)	31.94 ± 3.10 bA	27.45 ± 4.36 bA	36.89 ± 4.75 bA	49.43 ± 3.42 aA	46.94 ± 6.89 aA	53.02 ± 5.44 aA
Se (μg/g)	1.63 ± 0.18 aA	1.35 ± 0.08 aA	1.43 ± 0.08 aA	1.15 ± 0.12 bA	1.20 ± 0.02 bA	1.31 ± 0.21 aA

Note: All data are mean ± standard deviation ($n = 3$), and the test level $p = 0.05$. Lowercase letters indicate significant differences in tree age within different areas ($p \leq 0.05$), while uppercase letters indicate significant differences in tree age within the same area ($p \leq 0.05$).

Among different regions, from 0 to 5 years, there were significant differences in the contents of Fe, Mg, and B ($p \leq 0.05$). The content of Fe in the core area was higher than that in the expansion area, while the contents of Mg and B were higher in the expansion area. From 5 to 10 years, there were significant differences in the contents of Mg, B, and Se ($p \leq 0.05$), and the contents of Mg, B, and Se in the expansion area were all higher than those in the core area. From 10 to 20 years, there was a significant difference in the contents of Mg and B ($p \leq 0.05$), and the contents of Mg and B in the expansion area were still higher than those in the core area.

3.2. Yield Characteristics of Korla Fragrant Pear Orchards in Different Cultivation Areas and of Different Tree Ages

As shown in Figure 5, the characteristics of the fruit quantity, fruit quality, single-plant yield and yield of fragrant pears in different years and regions are as follows: In the core area of Figure 5A, the fruit quantity of fragrant pears aged 10–20 years is significantly higher than that of those aged 0–5 years and 5–10 years ($p \leq 0.05$). In the expansion area, the number of fragrant pear fruits aged 10–20 years was also significantly higher than that aged 0–5 years and 5–10 years ($p \leq 0.05$). In the core area of Figure 5B, the fruit quality of fragrant pears aged 10–20 years was significantly higher than that of those aged 0–5 years and 5–10 years ($p \leq 0.05$). In the expansion area, the fruit quality of fragrant pears aged 10–20 years was also significantly higher than that of those aged 0–5 years and 5–10 years ($p \leq 0.05$). In the core area, the single-plant yield of fragrant pears aged 10–20 years was significantly higher than that of those aged 0–5 years and 5–10 years ($p \leq 0.05$). In the expansion area, the single-plant yield of fragrant pears aged 10–20 years was also significantly higher than for those aged 0–5 years and 5–10 years ($p \leq 0.05$). In the core area of the yield chart D, the yield of fragrant pears aged 5–10 years was significantly higher than that of those aged 0–5 years and 10–20 years ($p \leq 0.05$). In the expansion area, the unit area yield of fragrant pears in the 10–20 years was significantly higher than for those aged 0–5 years and 5–10 years ($p \leq 0.05$). The Korla fragrant pears grown in the core area for 10–20 years performed the best in terms of fruit quantity, fruit quality, single-plant yield, and output.

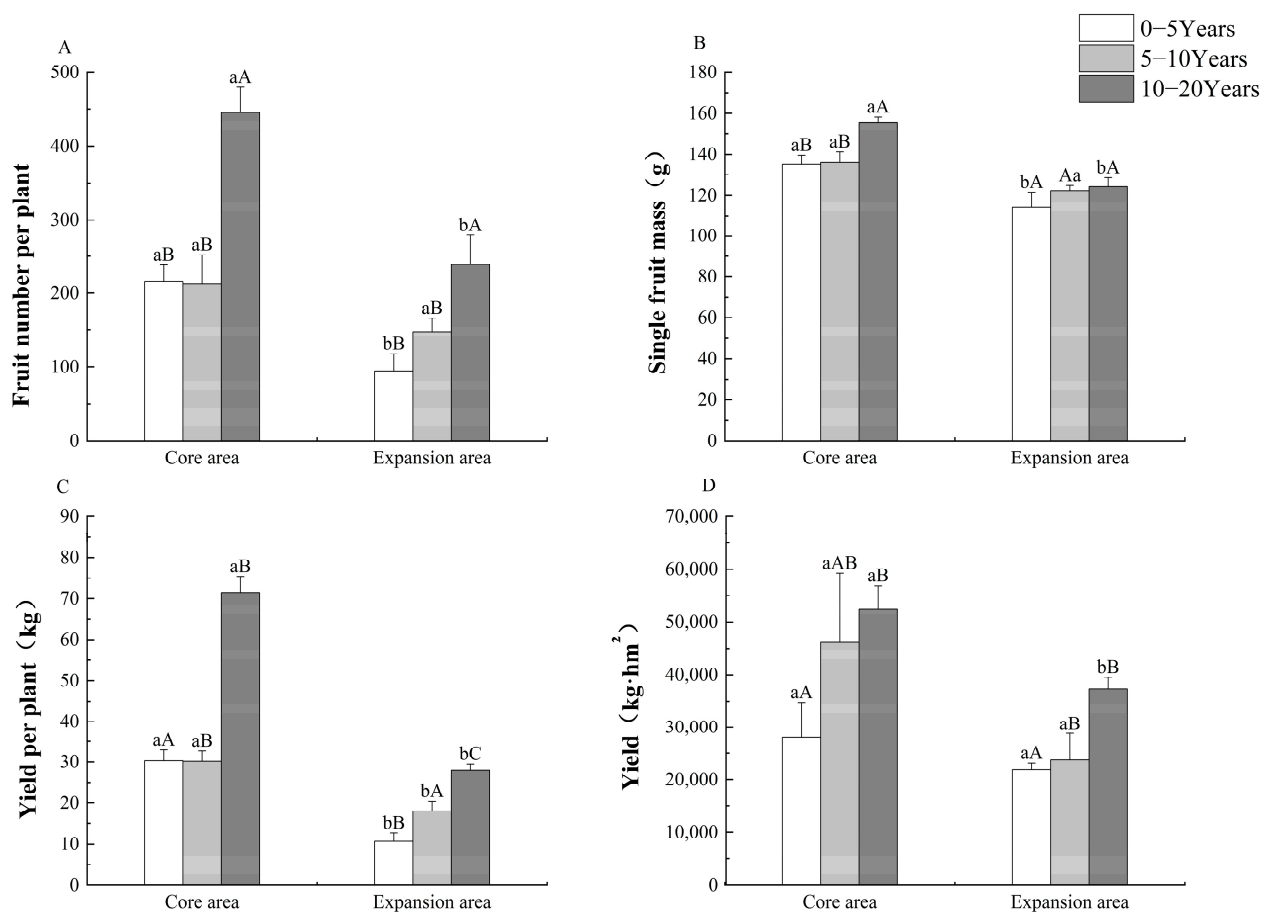


Figure 5. Yields of Korla fragrant pear orchards in different cultivation areas and at different tree ages: (A) fruit number per plant, (B) single-fruit mass, (C) yield per plant, and (D) yield. Note: Lowercase letters indicate significant differences in tree age within different areas ($p \leq 0.05$), while uppercase letters indicate significant differences in tree age within the same area ($p \leq 0.05$).

According to the classification standards for the yield grades of Korla fragrant pears in Table 2, orchards with trees aged 0–5 years in the core area are classified as low-yield orchards, those with trees aged 5–10 years are high-yield orchards, and those with trees aged 10–20 years are also high-yield orchards. The expansion area is classified as a low-yield orchard from 0 to 5 years old, from 5 to 10 years old, and from 10 to 20 years old. In the core area, fragrant pears with a tree age of 5–10 years and 10–20 years are classified as high-yield orchards, while those with a tree age of 0–5 years are considered low-yield orchards. All fragrant pears of all ages in the expansion area belong to low-yield orchards.

3.3. Analysis of Yield and Main Components of Soil Nutrients of Korla Fragrant Pear in Different Regions

The PCA Biplot, which reflects correlations among variables or between variables and samples, was utilized to analyze the relationship between yield and soil nutrients. As shown in Figure 6, the cumulative variance contribution rate of the first two principal components (PC 1, PC 2) for orchards aged 0–5 years was 72.80% (PC 1: 53.30%, PC 2: 19.50%). PC 1 exhibited strong positive loadings for AP, SOM, and yield. It indicates that in the orchard soil of 0–5 years, available phosphorus, soil organic matter, and yield are closely related to the positive direction of PC1, and they are the main contributors to the soil fertility and yield characteristics represented by PC1. PC1 showed strong negative loadings for EC, Ca, Mg, and B, suggesting weaker positive correlations or even negative associations with PC 1. For instance, higher EC values, indicating elevated soil salinity, may adversely affect soil fertility and crop growth, contradicting the characteristics represented by the positive direction of PC 1, which signifies favorable fertility and high yield. PC 2 displayed strong positive loadings for Zn, Cu, Mn, TN, AN, Se, and Fe. These elements, essential for various biochemical processes and microbial activities in soil, likely influence nutrient cycling and microbial dynamics. In contrast, PC 2 showed strong negative loadings for Ca, Mg, and B.

For orchards with 5–10 years tree age, the cumulative variance contribution rate of PC 1 and PC 2 reached 78.10% (PC 1: 53.60%, PC 2: 24.50%). PC 1 exhibited strong positive loadings for Mn, Cu, TN, SOM, AP, and Se, which are the key positive factors driving the differentiation of soil fertility characteristics in the mid-term orchard. Their synergistic effect helps to enhance the soil fertility level, thereby providing support for crop growth and yield formation. PC 1 showed a strong negative loading for pH, as elevated pH may reduce phosphorus availability by forming insoluble phosphates with cations like Ca^{2+} and Mg^{2+} , while also inhibiting microbial activity, thereby negatively impacting soil fertility and yield. PC 2 exhibited strong positive loadings for Fe, Zn, Ca, B, Mg, and EC, but a strong negative loading for yield.

In orchards of 10–20 years tree age, the cumulative variance contribution rate of PC 1 and PC 2 was 80.60% (PC 1: 52.30%, PC 2: 28.30%). PC 1 showed strong positive loadings for Ca, AP, SOM, TN, and yield. This indicates that it is the core positive driving factor for maintaining the long-term soil fertility stability of orchards and supporting crop yields, and is closely related to the comprehensive soil fertility characteristics represented by PC1. PC 1 also displayed a strong negative loading for pH. PC 2 exhibited strong positive loadings for Mn, Zn, Cu, Se, and Fe, suggesting their involvement in microbial activity and nutrient cycling, while showing strong negative loadings for Mg, B, AN, and EC, indicating negative associations with the microbial and nutrient cycling characteristics represented by the positive direction of PC 2.

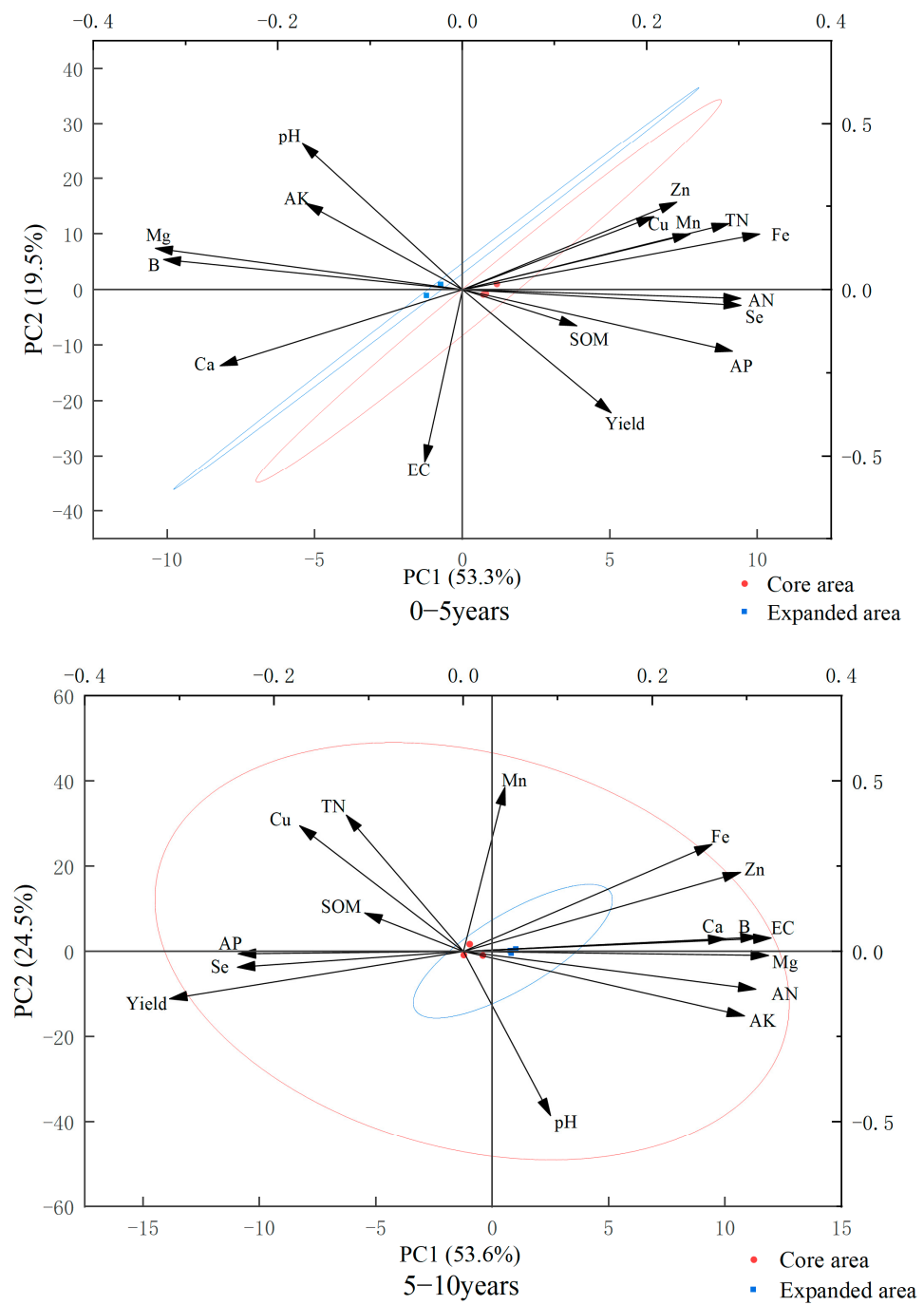


Figure 6. Cont.

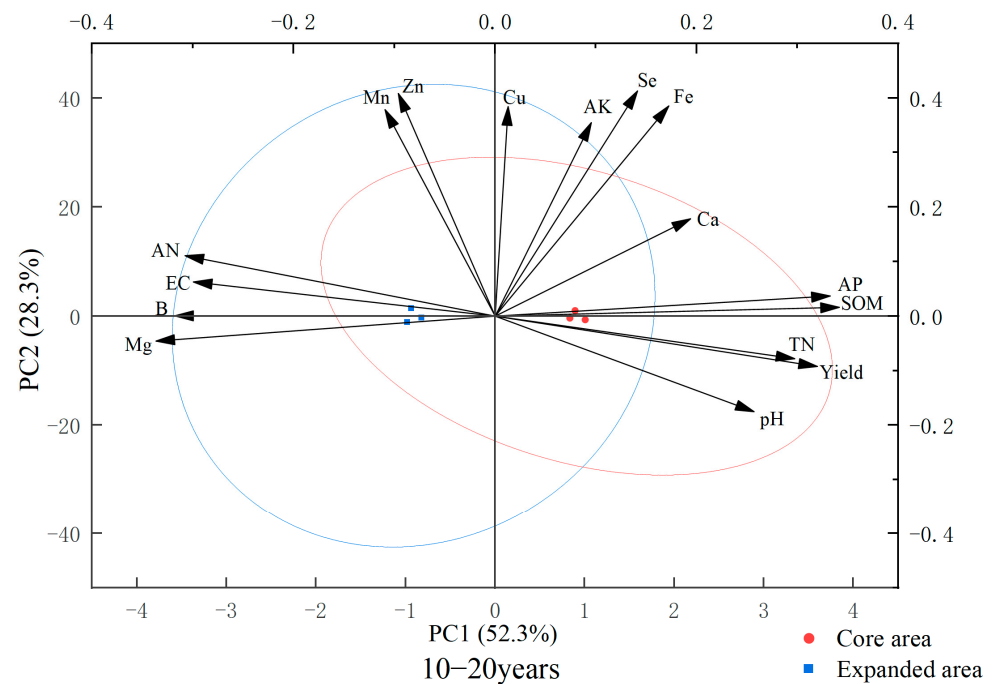


Figure 6. PCA biplot plots of soil nutrients and yields of Korla fragrant pear in different cultivation areas. Red circles denote the core area and blue triangles denote the expansion area.

4. Discussion

4.1. Soil Nutrient Characteristics in Different Cultivation Areas

SOM, TN, available nutrients, and trace elements in the soil play a significant role in enhancing soil fertility and productivity [15]. SOM and TN could improve soil structure, increase soil water retention and aeration capacity, provide rich nutrients for plants, and at the same time promote the activity of soil microorganisms, thereby enhancing soil fertility [16]. Available nutrients such as AN, AK, and AP were nutrients that plants can directly absorb and utilize, and are crucial for plant growth and development [17]. Trace elements in the soil such as Fe, Mn, Zn, and Cu played an irreplaceable role in enhancing soil fertility by acting as cofactors in enzymatic reactions and participating in key metabolic processes that promote nutrient cycling and the efficiency of plant nutrient absorption [18].

The contents of SOM and TN in the core area were significantly higher than those in the expansion area, which provided a richer source of nutrients for the pear trees in the core area and was conducive to the growth of the trees and the development of the fruits. In terms of available nutrients, the contents of AN, AK, and AP in the core area were generally better than those in the expansion area. Especially the content of AP was significantly higher in the core area at different tree age stages than in the expansion area. This indicates that the soil in the core area has a significant AP supply, while the expansion area had a considerable deficiency in phosphorus supply and may have needed to improve this situation through exogenous fertilization. The soil pH values remained stable in both regions and were within the range suitable for plant growth. However, the soil EC in the expansion area was relatively high, suggested that its salinization problem was more prominent. Especially in the tree age range of 5–10 years, the soil EC in the expansion area is significantly higher than that in other tree age ranges, indicating a higher risk of soil salt accumulation at this stage. This may limit the availability of soil nutrients and thereby affect the growth and development of pear trees [19]. According to the research of Xia et al. [20], the increase in stand age would have increased the availability and cycling of soil nitrogen, which is consistent with the phenomenon that the TN content of the soil in the core area increased with the increase in tree age in this study. Meanwhile, the soil of the

trees aged 10–20 years in the core area reached the highest grade in terms of AP content, indicating that it could provide sufficient phosphorus nutrition during the critical growth stage of fruit trees and meet the growth requirements of fruit trees. Micronutrients (Ca, Fe, Mn, Zn, Cu, etc.) played an irreplaceable role in plant metabolism, protein and nucleic acid formation, plant water use efficiency, and cell wall construction [21]. The contents of Ca, Fe, and Mn varied significantly among different tree ages in the core area. Among them, the content of Ca showed an upward trend with the increase in tree age. It indicates that as fruit trees grew, the absorption and accumulation of Ca were constantly increasing. This may be related to the growth of fruit tree roots and the enhanced absorption capacity of soil nutrients, or it may be that the soil's enrichment ability of Ca has improved during the long-term cultivation process [22]. This is contrary to the research results of Nirmal et al. [23] on mangoes of different tree ages, which might be caused by the different research subjects and regions. The content of Fe was the highest in 0–5 years and then decreased. This might be due to the fact that the soil environment in the orchard was more conducive to the accumulation and effective release of Fe in the early stage. With the increase in tree age and the change in soil conditions, the fixed or transformed form of Fe changed, resulting in a decrease in its content. The content of Mg reached its peak in 10–20 years, indicating that in the later stage of fruit tree growth, the soil's supply capacity for Mg increased. It might also be that the demand for Mg from fruit trees relatively increased, promoting the activation and release of Mg in the soil. In contrast, although the expansion area also showed a trend of increasing SOM and TN contents with the growth of tree age, the overall contents were still lower than those in the core area, and the increase was limited. This might be related to the fact that soil salinization limits the accumulation and availability of nutrients. Soil salinization could lead to the deterioration of soil structure and affect the soil's ability to adsorb and retain nutrients, thereby restricting the improvement of soil fertility [24]. There was a significant difference in Ca content among different tree ages in the expansion area and it showed an upward trend, while the differences in the contents of other elements were not significant. This indicates that in the expansion area, Ca is a nutrient element that is more prominently affected by tree age, and its content changes may be related to factors such as the parent material of the soil in the expansion area, the soil formation process, and fertilization and management measures in the orchard. Meanwhile, the relatively stable contents of other elements may have indicated that their supply or circulation is relatively balanced in the soil of the expansion area and is less affected by changes in tree age. The research of Chen et al. [25] also indicates that reasonable fertilization and soil management could effectively improve the ecological stoichiometric characteristics of the soil, enhance soil fertility, and thereby improve fruit quality. In addition, unreasonable soil management strategies, such as excessive fertilization and improper irrigation, may further exacerbate the problem of soil salinization, leading to a decrease in soil fertility and subsequently affected the quality and yield of fruits.

4.2. Yield Characteristics of Different Cultivation Areas

The results of this study showed that significant differences exist in single-fruit quality, fruit quantity per plant, and total yield of Korla fragrant pear across different cultivation regions. Fragrant pears with tree age of 10–20 years in the core area outperformed those with tree age of 0–5 years and 5–10 years in terms of fruit quantity, quality, and individual plant yield. Orchards with trees aged 0–5 years in the core area were classified as low-yield, while orchards with trees aged 5–10 years and 10–20 years fell into the high-yield category. In contrast, all orchards in the expansion area, regardless of tree age, were categorized as low-yield. Fei et al. [26] found that quality varied greatly among different production areas, which was consistent with the results of this study, both emphasizing the significant impact

of regional differences on yield. The superior performance of trees aged 10–20 years in the core area aligned with the physiological maturation patterns of fruit trees: as tree age increased, root systems developed, photosynthesis enhanced, and nutrient accumulation capacity improved. These physiological changes likely contributed to optimized fruit morphology and yield [27]. Conversely, the persistent low yields across all tree age groups in the expansion area suggested that soil conditions or other environmental factors in this region may have limited high yields. Potential issues in the expansion area included inadequate soil fertility, poor soil structure, uneven water supply, or pests and disease pressures. These factors may have synergistically restricted fragrant pear growth and yield [28].

4.3. Correlation Between Yield and Soil Nutrients in Different Cultivation Areas

Soil nutrients were the core content of soil fertility. Soil nutrients affected fruit yield [29]. In orchard soil from 0 to 5 years, PC 1 had strong positive loadings for AP, SOM, and yield, and strong negative loadings for EC, Ca, Mg, and B. PC 2 could withstand strong positive loadings for Zn, Cu, Mn, TN, AN, Se, and Fe, and strong negative loadings for Ca, Mg, and B. In the orchard soil for 5–10 years, PC 1 had a strong positive loadings for Mn, Cu, TN, SOM, AP, and Se and a strong negative load on pH value. PC 2 can withstand strong positive loadings for Fe, Zn, Ca, B, Mg, and EC and strong negative loadings on yield. For 10–20 years, PC 1 in orchard soil had strong positive loadings for Ca, AP, SOM, TN and yield, and strong negative loadings for pH value. PC 2 could withstand strong positive loadings for Mn, Zn, Cu, Se, and Fe and strong negative loadings for Mg, B, AN, and EC. This indicated that these soil nutrient elements largely determined the yield level of Korla fragrant pear [30]. The soil conditions in the core area are more conducive to the increase in fruit yield, while the expansion cultivation area had the problem of soil salinization, which affected the availability of soil nutrients and the absorption and utilization of nutrients by fruit trees, thereby limiting the yield of Korla fragrant pear. This was consistent with the result that Yao [31] conducted sampling and analysis of the soil and fruits in multiple apple orchards and found that the yield was positively correlated with most soil indicators. The soil conditions in the core area were more conducive to the increase in fruit yield. The contents of SOM, TN, and AP in its soil were relatively high, providing sufficient nutrient guarantee for the growth and fruit development of pear trees. However, the expansion area had a relatively prominent problem of soil salinization, which may reduce the availability of soil nutrients, affect the absorption and utilization of nutrients by fruit trees, and thereby limit the yield of Korla fragrant pear. Soil salinization can lead to the deterioration of soil structure and affect soil aeration and water permeability, and it is not conducive to the growth and development of fruit tree roots, due to the vast cultivation area and the variable climate and soil conditions in Xinjiang region [32].

5. Conclusions

Soil nutrients, as important ecological factors, exhibit different characteristics under different regions and cultivation conditions. This study focuses on the core area and expansion area of Korla fragrant pears in Xinjiang; the contents of SOM ($15.64\text{--}32.57\text{ g}\cdot\text{kg}^{-1}$), TN ($0.67\text{--}1.09\text{ g}\cdot\text{kg}^{-1}$), AP ($9.95\text{--}26.92\text{ mg}\cdot\text{kg}^{-1}$), Ca ($83.96\text{--}115.81\text{ mg/g}$) in the core area were significantly higher than those in the expansion area, and the elemental balance was excellent. It provides a material basis for its high yield ($52,439.41\text{ kg}\cdot\text{hm}^2$). PCA analysis further confirms that Ca, AP, SOM, and TN are the dominant factors driving yield in orchards with tree ages of 10–20 years, and the cumulative variance contribution rate reaches 80.60%. Although the soil nutrients in the expansion area increase with the growth of tree age, salinization ($\text{EC } 0.36\text{--}1.16\text{ dS/m}$) limits the availability of nutrients. Soil salinization (high EC) and excessive Mg and B elements lead to nutrient imbalance, which become

the main limiting factors for its low yield (34,825.69 kg·hm²). In the future, the core area can further optimize the elemental balance by maintaining the existing soil conditions, increasing the application of organic fertilizers and balanced fertilization (supplementing Ca, Se). In the expansion area, priority should be given to solving the problem of soil salinization, controlling the input of Mg and B, and increasing the application of Ca, P fertilizers, and organic fertilizers. These measures will improve soil fertility and elemental balance, thereby enhancing the yield and quality of fragrant pear. Whether in the core area or the expansion area, the balance of soil elements (avoiding excessive or deficient single elements) and the prevention and control of salinization are both at the core of maintaining long-term yields. This principle has universal reference significance for soil management in other fruit tree cultivation areas and also provides data support for the formulation of technical regulations for precise fertilization in the orchard area. For similar orchards that support the “region-specific policy” smart agriculture model, the idea can be extended to the soil nutrient management of other cash crops.

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