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Effects of Green Manure Application on Postharvest Quality and Soil Fertility of Korla Fragrant Pear

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Simple Summary

Korla fragrant pear is a signature fruit of Xinjiang, China, prized for its aroma and sweetness. However, its quality declines rapidly after harvest, causing significant economic losses. This study investigated whether planting green manure crops—sweet clover or alfalfa—in orchards could improve the postharvest quality of the pears. We found that alfalfa green manure helped maintain higher nutritional stability during cold storage, whereas sweet clover promoted sugar accumulation and fruity aroma. Using advanced statistical models, we also showed that the type of green manure changes how soil nutrients are transferred to fruit quality. These findings suggest that growers can choose specific green manure species to target desired postharvest traits, offering a sustainable soil management strategy for pear orchards.

Abstract

Postharvest quality deterioration of Korla fragrant pear (*Pyrus sinkiangensis* Yu) severely constrains its market value, yet the regulatory role of pre–harvest soil management in shaping postharvest performance remains poorly understood. This study investigated how green manure species modulate postharvest quality trajectories and their underlying soil–fruit linkages. Three pre–harvest treatments were imposed: control (CK), sweet clover (CM), and alfalfa (MX). Fruits were harvested and stored at 4 °C, with sampling at 1, 5, 10, 15, and 20 d. A critical quality transition was identified at 15 d, characterized by the concurrent peaking of soluble sugars, organic acids, vitamin C, and anthocyanins alongside an optimal sugar–acid ratio. Beyond this inflection point, CM and MX diverged markedly: CM enhanced soluble sugar accumulation, anthocyanin retention, and ester volatile production—most notably hexyl acetate, which increased over 14.4–fold—thereby generating a pronounced fruity aroma bouquet. Conversely, MX sustained higher amino acid and vitamin C levels and conferred superior late–storage stability, evidenced by a threefold lower coefficient of variation in sugar–acid ratio relative to CK. partial least squares structural equation modeling (PLS–SEM) revealed soil fertility as the principal driver of fruit quality, but the fidelity of soil–to–fruit transmission was species–dependent. MX achieved near–complete explanatory power ($R^2= 0.971$), whereas CM exhibited attenuated transmission fidelity ($R^2= 0.777$), with network analysis further indicating that CM inverted the polarity of key soil–fruit correlations. These findings demonstrate that green manure identity governs postharvest quality through divergent soil–fruit coupling pathways: alfalfa optimizes nutrient transmission efficiency and stabilizes nutritional quality, whereas sweet clover promotes sugar–aroma accumulation at the cost of reduced soil–fruit conversion fidelity. Species–specific green manure selection thus offers a viable strategy for targeted modulation of postharvest traits in Korla fragrant pear.

Keywords: Korla fragrant pear; green manure; postharvest quality; critical quality transition; soil–fruit coupling; partial least squares structural equation modeling (PLS–SEM)

1. Introduction

Korla fragrant pear (*Pyrus sinkiangensis* Yu) is a signature product of Xinjiang's characteristic fruit industry, renowned both domestically and internationally for its unique aroma, delicate texture, and excellent sugar–acid ratio[1,2]. It serves as a pivotal pillar industry for rural revitalization in southern Xinjiang. However, fragrant pear is a typical climacteric fruit characterized by vigorous postharvest respiratory metabolism. Under ambient storage conditions, it rapidly exhibits peel yellowing, flesh softening, flavor deterioration, and rot loss, leading to a sharp decline in marketability[3,4] Postharvest loss rates of pear fruit in China are high, with quality deterioration being the primary cause [1]. Orchard soil management is a critical pre–harvest factor influencing postharvest fruit quality. Tree nutritional status not only determines the initial quality at harvest but also indirectly regulates postharvest senescence through its effects on cell structural integrity, antioxidant system activity, and energy metabolism levels[5]. Green manure, as a core technology of ecological orchard cultivation, can significantly improve soil fertility and tree nutritional reserves through biological nitrogen fixation[6], organic matter return[7], and rhizosphere microecological regulation [8]. However, existing studies have predominantly focused on the effects of green manure on fruit yield and appearance quality during the growing season, while tracking studies on how green manure application influences postharvest physiological metabolism and quality maintenance through the synergistic effects of the "soil–tree–fruit" system remain relatively scarce.

Orchards, as an important component of agricultural production in China, face prominent challenges including soil quality degradation under long–term cultivation [9], non–point source pollution caused by excessive chemical fertilizer application [10], inconsistent fruit quality across orchards and years, and fragile ecological environments in major producing regions. The long–term application of traditional clean–cultivation practices in orchards has triggered numerous issues constraining sustainable orchard industry development [11], among which soil quality degradation is particularly pronounced [12]. This is manifested as accelerated soil acidification [9], depleted organic matter content [12], and destruction of aggregate structure [13], which not only significantly reduces soil nutrient supply capacity and water–fertilizer retention performance but also exacerbates tree root growth obstacles, indirectly leading to inconsistent fruit quality [11] and severely affecting the economic benefits of orchard production [11]. Green manure, as a natural green fertilizer material, possesses multiple functions including soil improvement, nutrient supply, and ecological restoration[14]. Its scientific and rational application in orchards has been widely recognized by domestic and international scholars as an effective approach to resolving the aforementioned development dilemmas[11,15] and promoting the green transformation of the orchard industry[11,16]. The ameliorative effects of green manure on orchard soil and tree nutrition are ultimately reflected through fruit quality. Fruit quality depends not only on the instantaneous state at harvest but is also closely related to its maintenance capacity during postharvest storage [17]. Postharvest fruit quality is a multidimensional concept encompassing appearance, nutrition, and flavor [18]. Among these, the sugar–acid ratio and vitamin C content determine nutritional quality, anthocyanin content is associated with coloration and antioxidant capacity, and volatile aroma components (esters, aldehydes, terpenes, etc.) represent the core indicators of flavor quality [19]. There exists a quality window period, referring to a specific timeframe when comprehensive quality reaches optimal balance. Clarifying the dynamic variation patterns and peak occurrence times of postharvest quality of fragrant pear under green manure treatments holds important practical significance for guiding optimal harvest timing and marketing [20]. Furthermore, the formation of flavor substances is closely related to tree carbon–nitrogen metabolism and secondary metabolic pathways; green manure may promote the synthesis and accumulation of characteristic aroma components by improving tree nutritional status [21]. The soil–plant system synergistic effect is key to understanding the postharvest regulatory mechanism of green manure. Soil organic matter, nutrient availability, and enzyme activity not only directly affect tree growth and development but may also indirectly influence postharvest storability and quality maintenance capacity by regulating fruit cell wall components, membrane lipid peroxidation levels, and antioxidant enzyme activity [22]

[23]. However, existing studies mostly treat soil fertility and fruit quality as independent objects of separate investigation, lacking in–depth analysis of their association mechanisms.

In summary, the effects of green manure application on the postharvest storage quality of Korla fragrant pear and its soil–fruit synergistic regulatory mechanism remain unclear. Based on this, the present study established three treatments—control (CK), sweet clover (Melilotus officinalis, CM), and alfalfa (Medicago sativa, MX)—and adopted a standardized storage protocol at 4 °C with a dynamic sampling strategy (0, 5, 10, 15, and 20 d). This study aims to: (1) clarify the influence patterns of different green manure treatments on the dynamic changes of postharvest appearance quality, nutritional quality, and flavor substances of fragrant pear, and determine the optimal time window for quality maintenance; (2) elucidate the ameliorative effects of green manure application on rhizosphere soil fertility; and (3) analyze the association characteristics between soil and fruit quality indicators and the synergistic pathways of green manure regulation.

2. Materials and Methods

2.1. Experimental Materials and Site Description

The experiment was conducted at the Awaiti Farm in Bayingolin Mongol Autonomous Prefecture (86°04′ E, 41°41′ N), a core production area of Korla fragrant pear in Xinjiang, China. The experimental site is located at an altitude of 950 m, with an annual sunshine duration of 2,990 h and a frost–free period of 210 d, belonging to a warm temperate continental arid climate. The soil type is irrigation–silted soil with a loam texture, and the baseline fertility was uniform across the site. The test trees were 15–year–old Korla fragrant pear , with a planting spacing of 4 m × 5 m and consistent conventional management practices.

Green manure materials included sweet clover (Melilotus officinalis, CM) and alfalfa (Medicago sativa, MX), which were sown in April 2025. In July 2025, at the flowering stage, the whole plants were incorporated into the soil at a depth of 15–20 cm. The control (CK) treatment did not plant green manure; instead, naturally occurring weeds between tree rows were regularly mowed and removed.

2.2. Experimental Design

The field experiment was conducted using a single–factor randomized complete block design with three treatments: CK (control), CM (Melilotus officinalis), and MX (Medicago sativa).

Fruits were harvested in mid–September 2025 according to commercial standards. For each treatment, ten fruit trees with consistent growth vigor were selected, and 30 fruits were picked from the middle part of the canopy periphery of each tree, resulting in a total of 900 fruits. After harvest, the fruits were pre–cooled for 24 h, then packed into perforated plastic baskets (30 fruits per basket), transported to the laboratory, and stored in a constant–temperature light incubator at 4 ± 0.1°C with a relative humidity of 85%–90%. Samples were collected at 1, 5, 10, 15, and 20 days of storage. At each time point, ten fruits were randomly taken from each treatment. Initial quality was measured on day 1, and postharvest dynamic changes were assessed from day 5 to day 20. Fresh weight, appearance, and nutritional quality were determined immediately after sampling.

Soil samples were collected twice: before green manure incorporation (April 2025) and at fruit harvest (September 2025). Within each treatment, five trees were selected following an “S”–shaped pattern. Soil samples (0–20 cm rhizosphere soil) were collected using a soil auger at a point 10 cm inside the edge of the canopy projection. For each tree, five subsamples were taken and pooled into one composite sample. After passing through a 2 mm sieve and mixing, the soil samples were stored at 4°C, and all analyses were completed within one week.

2.3. Determination Indicators and Methods

2.3.1. Fruit Quality

Appearance quality: Peel color was measured using a colorimeter (CR–400, Konica Minolta, Japan) at three equatorial positions per fruit, and the average was calculated. Chroma (C) was calculated as $C = (a^2 + b^2)^{1/2}$, and hue angle (h°) was calculated as $h° = \arctan(b^*/a^*)$.

Fresh weight: Single fruit fresh weight was measured using an electronic analytical balance (ME104E, Mettler Toledo, Switzerland). Twenty uniform–sized, pest– and disease–free fruits were selected per treatment, individually numbered, and used as fixed observation objects. Measurements were taken at 0, 5, 10, 15, and 20 d.

Organic acids: Organic acid content was determined by high–performance liquid chromatography (HPLC). Briefly, 2 g of sample was placed in a 50 mL centrifuge tube and weighed. Then, 8 mL of 0.2% metaphosphoric acid solution was added, vortexed for 1 min, and ultrasonicated at room temperature for 20 min. The mixture was filtered and brought to a final volume of 10 mL. A 1.2 mL aliquot of the sample solution was centrifuged at 10,000 × g for 10 min, and 600 μL was transferred into two HPLC vials. The sample was injected into an HPLC system equipped with an ION–300 ion–exchange column (300 mm × 7.8 mm, 8 μm) and a UV detector. The mobile phase was 50 mmol/L potassium dihydrogen phosphate solution (pH 2.5) at a flow rate of 1.0 mL/min, column temperature of 30 °C, and detection wavelength of 210 nm. Organic acid contents were quantified by comparison with standard substances using the external standard method.

Free amino acids: Amino acid content was determined by high–performance liquid chromatography with ultraviolet detection (HPLC–UV). Pear samples were crushed, and 1.0 g was weighed and brought to 25 mL with 5% trichloroacetic acid (5 g/100 mL). The mixture was homogenized, ultrasonicated for 20 min, allowed to stand for 2 h, and filtered. A 1 mL aliquot of filtrate was passed through a 0.45 μm aqueous membrane filter into an HPLC vial. Internal standard norleucine was added to the sample solution, followed by pre–column derivatization with phenyl isothiocyanate (PITC). HPLC–UV analysis was performed using a Venusil–AA amino acid analysis column (100 Å, 4.6 mm × 250 mm, 5 μm) under the following conditions: detection wavelength 254 nm, column temperature 40 °C. Mobile phase A was sodium acetate–acetonitrile solution (pH 6.5), and mobile phase B was 80% acetonitrile. The gradient elution program was as follows: 0–0.1 min, 0% B; 0.1–14 min, 20% B; 14–33 min, 34% B; 33–41 min, 100% B; 41–49 min, 0% B. The injection volume was 2 μL, and the flow rate was 1 mL/min. Quantitative analysis of each amino acid was performed by the external standard method, and the content of each amino acid in the sample was calculated according to the standard curve.

Anthocyanins: Total anthocyanin content was determined by the pH differential method. Fruit samples (2.0 g), with stems removed and surfaces wiped clean, were added to 20 mL of 85% hydrochloric acid–methanol solution (85:15, V/V) and extracted in the dark with shaking for 20 min. Extraction was repeated twice, the filtrates were combined and brought to 50 mL, and the filtrate was collected after filtration. A 2.0 mL aliquot of extract was brought to 10 mL with potassium chloride buffer (0.025 mol/L, pH 1.0) and sodium acetate buffer (0.4 mol/L, pH 4.5), respectively. After equilibration in the dark for 30 min, absorbance was measured at 510 nm and 700 nm. Total anthocyanin content was expressed as cyanidin–3–O–glucoside equivalents and calculated using the formula: Anthocyanin content (mg/g) = $(A \times MW \times DF \times V) / (\varepsilon \times L \times m)$, where $A = (A_{510} - A_{700})_{p}H_{1.0} - (A_{510} - A_{700})_{p}H_{4.5}$, MW = 449.2, DF is the dilution factor, and $\varepsilon = 26{,}900$. Each sample was measured in triplicate.

Vitamin C (Vc): Vitamin C content was determined by titration with 2,6–dichlorophenolindophenol sodium salt (DCIP). Fruit samples (5.0 g), with stems removed and surfaces wiped clean, were added to 20 mL of 2% oxalic acid solution and ground into a homogenate under ice–bath conditions. The homogenate was transferred to a 50 mL volumetric flask, brought to volume with 2% oxalic acid solution, shaken well, and filtered. Exactly 10 mL of filtrate was pipetted into a conical flask and titrated with standardized DCIP solution until a pink color persisted for 15 s.

A blank control was prepared using 2% oxalic acid solution. Each sample was measured in triplicate, and results were expressed as mg/100 g fresh weight.

Volatile aroma components: Volatile aroma components were determined by headspace solid–phase microextraction coupled with gas chromatography–mass spectrometry (HS–SPME–GC–MS). HS–SPME conditions: 2 g of crushed pear was placed in a 20 mL headspace vial, and 1 μL of 2–methyl–3–heptanone internal standard solution (118.2 μL/mL) was added immediately. The vial was sealed with a polytetrafluoroethylene/butyl rubber septum. After equilibration in a 60 °C water bath for 7 min, extraction was performed using an SPME fiber (50/30 μm DVB/CAR/PDMS) for 30 min, followed by desorption at 250 °C for 7 min. High–purity helium was used as the carrier gas at a flow rate of 1 mL/min. Chromatographic conditions: an SH–WAX capillary column (30 m × 0.25 mm × 0.25 μm) was used. The column temperature program was as follows: held at 40 °C for 3 min, ramped to 100 °C at 6 °C/min, and finally ramped to 250 °C at 10 °C/min, held for 5 min. Both the detector and injector temperatures were 250 °C, with splitless injection. MS conditions: EI ion source, electron energy 70 eV, mass scan range 35–450 m/z. Ion source and interface temperatures were both 250 °C. Volatile compounds were identified using the Wiley standard mass spectral library (NIST17 and 17s) and relevant literature. In the three replicate groups of this experiment, compounds with similarity > 70% were considered valid substances. If a valid substance was consistently detected in all three replicate groups, it was designated as a characteristic valid volatile compound of the sample and included in subsequent quantitative and differential analysis. If a valid substance was consistently detected in only two replicate groups, it was determined whether the compound at the same retention time in the third group was an isomer of the other two; if so, its name was modified to be consistent with the other two groups and included in subsequent analysis. The content of each volatile flavor component (μg/kg) was calculated as: (peak area of each component × content of internal standard) / (sample weight × peak area of internal standard).

2.3.2. Soil Fertility

Soil pH was measured using a pH meter. Electrical conductivity (EC) was measured using a conductivity meter. Soil organic matter was determined by the potassium dichromate oxidation–external heating volumetric method. Total nitrogen was determined by the Kjeldahl method. Alkali–hydrolyzable nitrogen was determined by the alkali–hydrolyzed diffusion method. Available phosphorus was determined by the molybdenum–antimony resistance spectrophotometric method. Available potassium was determined by flame photometry.

2.4. Data Processing

Data were organized using Microsoft Excel 2019 and statistically analyzed using R v4.5.1 (R Core Team, 2024). Differences among treatments at each storage time point were compared by one–way analysis of variance (ANOVA), followed by Duncan's multiple range test ($p < 0.05$). Principal component analysis (PCA) was performed using the FactoMineR package (Lê et al., 2008), and heatmaps were generated using the pheatmap package (Kolde, 2019). Figures were plotted using Origin 2023 (OriginLab, Northampton, MA, USA).

3. Results

3.1. Effects of Green Manure Application on Postharvest Nutritional Quality

3.1.1. Dynamic Changes in Fruit Quality Indicators

As shown in Figure 1, under 4 °C storage conditions, green manure treatments exhibited significant regulatory effects on the postharvest weight loss rate and five nutritional quality indicators of Korla fragrant pear, with each indicator showing distinct temporal dynamic variation patterns.

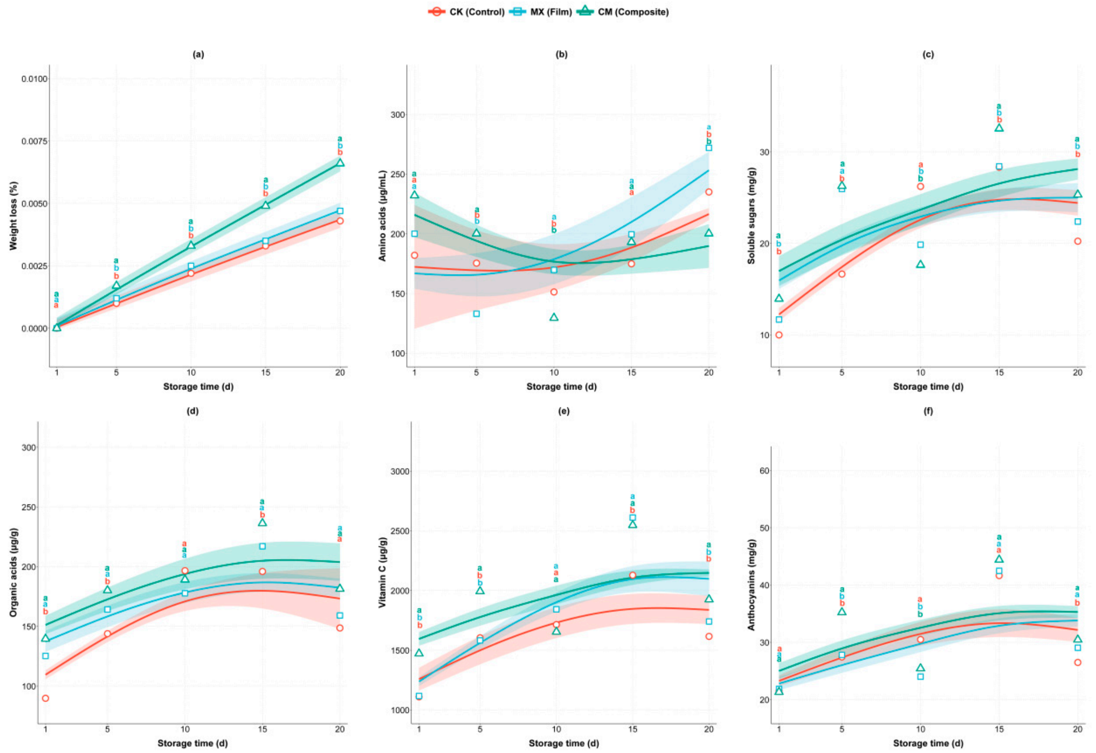

Figure 1. Effects of green manure treatments on fruit quality indicators of Korla fragrant pear during storage. (A) Weight loss rate; (B) Amino acids; (C) Soluble sugars; (D) Organic acids; (E) Vitamin C; (F) Anthocyanins. Note: Shaded areas indicate ± SD range. Different lowercase letters indicate significant differences among treatments at the same storage time point (Duncan's multiple range test, $p < 0.05$).

The weight loss rate (Figure 1A) showed a continuous upward trend with prolonged storage time, increasing from 0% to 0.43%, 0.66%, and 0.47% in the control (CK), alfalfa green manure (MX), and sweet clover green manure (CM) treatments, respectively. The MX treatment exhibited the highest weight loss rate, which may be attributed to the stronger metabolic activity of fruits in this treatment.

Amino acid content (Figure 1B) displayed a fluctuating trend characterized by an initial decrease, followed by an increase, and a subsequent decrease again. All three treatments reached peak values at 15 d of storage, with the MX treatment (272.02 μg/mL) and CM treatment (200.24 μg/mL) being significantly higher than the CK treatment (235.07 μg/mL). Notably, the amino acid content in the MX treatment was significantly higher than that in the other two treatments at the early storage stage (Day 1), indicating that alfalfa green manure may have promoted the pre–harvest accumulation of amino acids.

Soluble sugar content (Figure 1C) showed an overall upward trend. The CM treatment reached its maximum value at 20 d of storage (32.54 mg/g), representing a 133.4% increase compared with the initial value (13.94 mg/g). The MX and CK treatments reached their peak values at 15 d (28.41 mg/g and 28.32 mg/g, respectively). All three treatments maintained relatively high sugar levels during 15–20 d, indicating that this period represents the optimal stage for fruit sweetness.

Organic acid content (Figure 1D) followed a trend similar to that of amino acids, with all treatments reaching peak values at 15 d. The CM treatment exhibited the highest peak value (236.33 μg/g), which was 20.6% higher than that of the CK treatment (196.01 μg/g), while the MX treatment reached 217.13 μg/g. The coordinated changes in organic acids and soluble sugars collectively determined the dynamic changes in the sugar–acid ratio.

Vitamin C content (Figure 1E) accumulated continuously during storage, with all three treatments reaching peak values at 15 d. The MX treatment (2611.64 μg/g) and CM treatment (2547.24 μg/g) were significantly higher than the CK treatment (2128.31 μg/g), representing increases of 22.7%

and 19.7%, respectively, indicating that green manure treatments significantly enhanced the antioxidant capacity of the fruits.

Anthocyanin content (Figure 1F) also peaked at 15 d. The CM treatment (44.41 mg/g) and MX treatment (42.49 mg/g) were 6.6% and 2.0% higher than the CK treatment (41.65 mg/g), respectively, suggesting that green manure treatments exerted a slight promoting effect on peel coloration.

3.1.2. Dynamic Changes in Fruit Sugar–Acid Ratio

As shown in Figure 2, different green manure treatments exerted significant regulatory effects on the dynamic changes in the sugar–acid ratio of Korla fragrant pear during storage. At 5 d of storage, no significant differences were observed among the groups. At 10 d, the sugar–acid ratios in the MX treatment (158.64 ± 15.46) and CM treatment (146.05 ± 13.11) were significantly higher than that in the CK treatment (115.71 ± 3.36) ($p < 0.05$), representing increases of 37.1% and 26.2%, respectively, indicating that both green manure treatments could significantly improve fruit flavor quality during the mid–storage period. At 15 d, the CM treatment decreased significantly to 93.20 ± 8.53, which was 30.2% lower than that of the CK treatment ($p < 0.01$), whereas no significant difference was observed between the MX treatment and the CK treatment, suggesting that the regulatory effect of sweet clover green manure was relatively short–lived. At 15–20 d, the groups tended to converge; however, the coefficient of variation (CV) in the MX treatment (3.4%) was significantly lower than that in the CK treatment (19.6%), indicating that alfalfa green manure could improve the stability of the sugar–acid ratio during the late storage period. In conclusion, alfalfa green manure exhibited a stronger and more persistent positive regulatory effect on the sugar–acid ratio of Korla fragrant pear.

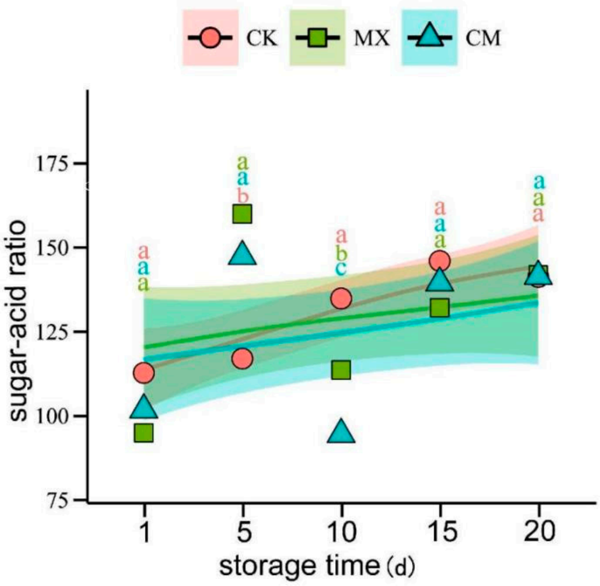

Figure 2. Dynamic changes in the sugar–acid ratio of Korla fragrant pear under different green manure treatments. Note: Different lowercase letters indicate significant differences at the same storage time point (Duncan's multiple range test, $p < 0.05$).

3.2. Effects of Green Manure Application on Postharvest Appearance Quality of Korla Fragrant Pear

3.2.1. Dynamic Changes in Peel Coloration

Peel coloration is an important indicator reflecting postharvest appearance quality and senescence degree of fruits. As shown in Figure 3, under 4 °C storage conditions, the CIE Lab* color parameters of peel in Korla fragrant pear under different green manure treatments exhibited regular dynamic changes, with no significant differences in the overall trends among treatments ($P > 0.05$).

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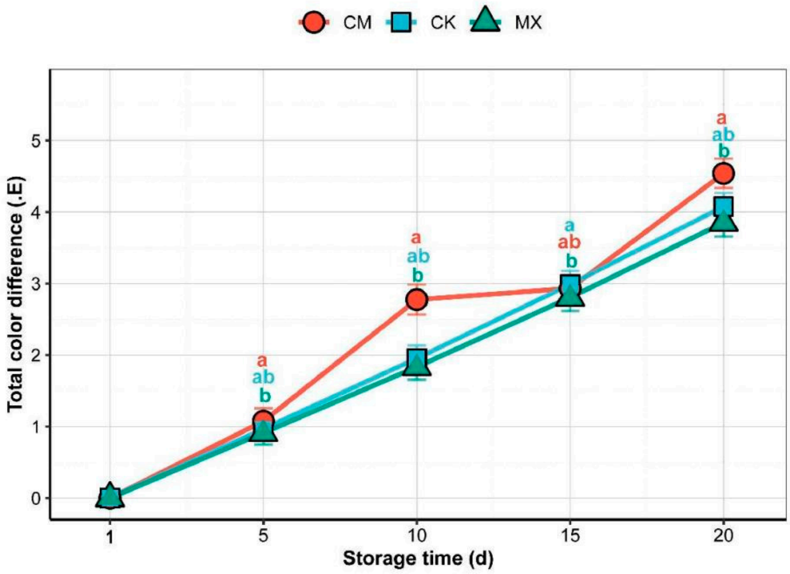

Figure 3. Effects of green manure treatments on postharvest peel color parameters of Korla fragrant pear. Note: Different lowercase letters indicate significant differences at the same storage time point (Duncan's multiple range test, $p < 0.05$).

As shown in Figure 3, the effect of green manure treatments on the total color difference (ΔE) of postharvest peel in Korla fragrant pear gradually became apparent with prolonged storage time. During storage, ΔE values in all treatment groups showed an upward trend, indicating that peel coloration gradually deviated from the initial state. At 20 d, the ΔE values in the sweet clover green manure (CM), control (CK), and alfalfa green manure (MX) treatments were 4.54, 4.08, and 3.85, respectively, ranking as CM > CK > MX; however, the differences among treatments did not reach significant levels (P > 0.05). This indicates that the preservation effects of both green manure treatments on postharvest peel coloration of Korla fragrant pear were comparable to those of the control, and although the total color difference in the alfalfa green manure treatment was slightly lower than that in the other treatments, the advantage was not pronounced. The failure of green manure treatments to significantly improve fruit appearance quality may be attributed to the fact that postharvest senescence of Korla fragrant pear is primarily regulated by ethylene, coupled with a mismatch between the timing of green manure nutrient release and the developmental requirements of the fruit.

3.3. Effects of Green Manure Treatments on Fruit Flavor Substances

3.3.1. Effects of Green Manure Treatments on Characteristic Aroma Components of Korla Fragrant Pear During Storage

Comprehensive analysis indicated that, based on the dynamic monitoring results of the sugar–acid ratio and fruit nutritional indicators, 15 d of storage (the 4th sampling batch) was identified as the postharvest quality window period of Korla fragrant pear. At this time point, soluble sugar content reached peak values (32.54 mg/g for CM and 28.41 mg/g for MX), and the sugar–acid ratio recovered to an optimal balance (131–138). The contents of amino acids, vitamin C, and anthocyanins in the fruits were all at high levels throughout the entire storage period. During this period, the appearance quality, nutritional quality, and flavor harmony of the fruits reached the optimal balance, with the highest commercial value. Therefore, fruits at 15 d of storage were used as the material for subsequent volatile aroma component analysis and soil–fruit quality association studies, to ensure data representativeness and comparability of results.

Aroma substances are the key determinants of fruit flavor quality. When soluble sugars, organic acids, anthocyanins, and vitamin C were all within the quality window period at 15 d of storage, HS–

SPME–GC–MS analysis was performed on Korla fragrant pear under different green manure treatments. A total of 32 volatile aroma components were detected, including alcohols, esters, aldehydes, ketones, phenols, and alkanes.

As shown in Figure 4, green manure application significantly altered the postharvest volatile aroma metabolic profile of Korla fragrant pear. CM and MX clustered into one group, while CK formed a separate cluster. A total of 23 aroma components were identified, with alcohols and esters being the predominant constituents. The CM treatment exhibited the highest contents of (E)–2–hexen–1–ol and ethyl benzoate, presenting a composite aroma of green, fruity, and sweet notes; the MX treatment was enriched in esters such as ethyl hexanoate and hexyl acetate, presenting a pure and intense fruity aroma; the CK treatment displayed an overall bland flavor profile. Heatmap clustering revealed that alcohols and esters were highly expressed under green manure treatments, representing the core target substances for quality improvement. These results indicate that green manure promotes the accumulation of characteristic flavor substances by regulating aroma metabolic pathways, with CM and MX forming differentiated flavor characteristics.

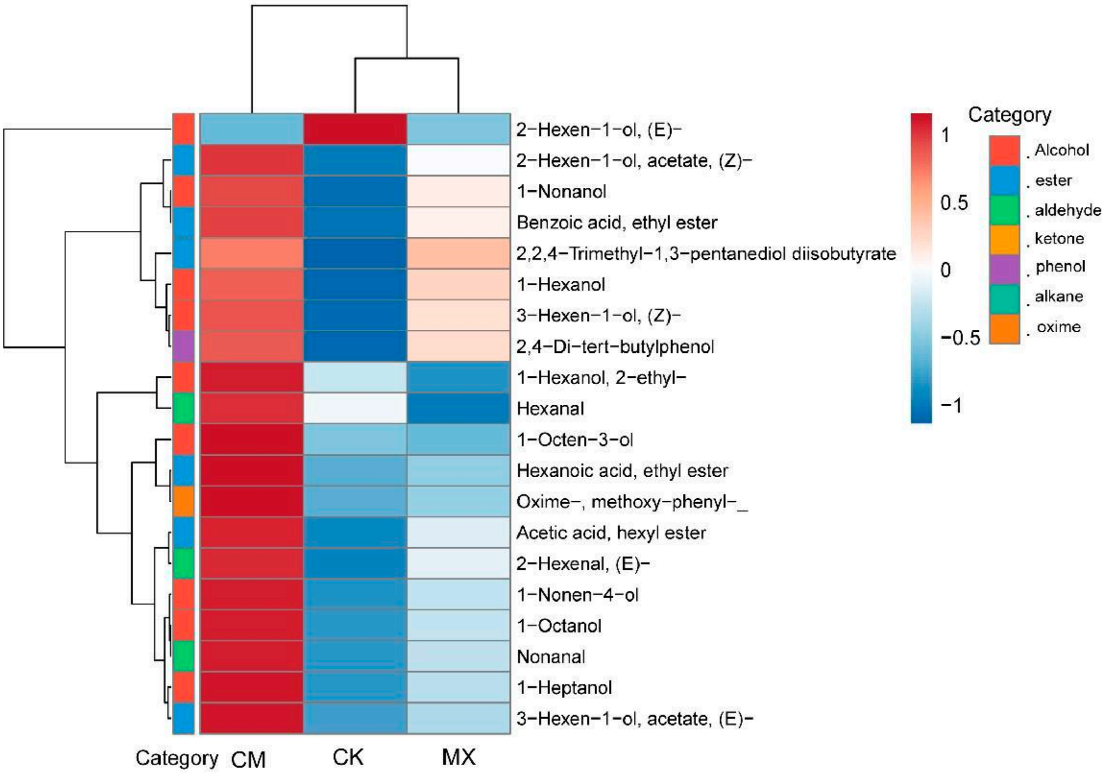

Figure 4. Heatmap and hierarchical cluster analysis of flavor substances in Korla fragrant pear under different green manure treatments.

3.3.2. Effects of Green Manure Treatments on Characteristic Aroma Components During Storage

To intuitively demonstrate the influence of green manure treatments on characteristic aroma substances of Korla fragrant pear, six representative compounds were selected in this study based on dual criteria of content levels and flavor contribution.

As shown in Figure 5, the sweet clover green manure treatment (CM) significantly enhanced the contents of characteristic aroma components, exhibiting a pronounced aroma–enhancing effect. Among alcohols, the content of 1–hexanol reached 3500.95 μg/kg, representing increases of 138.3% and 29.7% compared with the control (1469.74 μg/kg) and the alfalfa green manure treatment (2699.49 μg/kg), respectively ($p < 0.05$). The content of (Z)–3–hexen–1–ol (leaf alcohol) reached 159.33 μg/kg, which was 23.3 and 2.9 times that of the control and the alfalfa green manure treatment, respectively, with differences reaching extremely significant levels. Among esters, the content of hexyl acetate was as high as 3755.83 μg/kg, representing a 14.4–fold increase compared with the control and a 4.3–fold increase compared with the alfalfa green manure treatment ($p < 0.05$). The contents of ethyl hexanoate and (E)–3–hexen–1–yl acetate were 347.15 μg/kg and 213.20 μg/kg, respectively, both significantly higher than those in the other two groups ($p < 0.05$). Among aldehydes, the content of (E)–2–hexenal reached 257.57 μg/kg, representing a 119.7% increase compared with the control ($p < 0.05$). In contrast, the alfalfa green manure treatment (MX) exhibited intermediate contents for most aroma substances between the control and the sweet clover green manure treatment, with no significant differences from the sweet clover green manure treatment only in 1–hexanol and (E)–2–hexenal ($p > 0.05$), indicating that the two green manure treatments exhibited divergent regulatory effects on fruity aroma substances (aldehydes and alcohols).

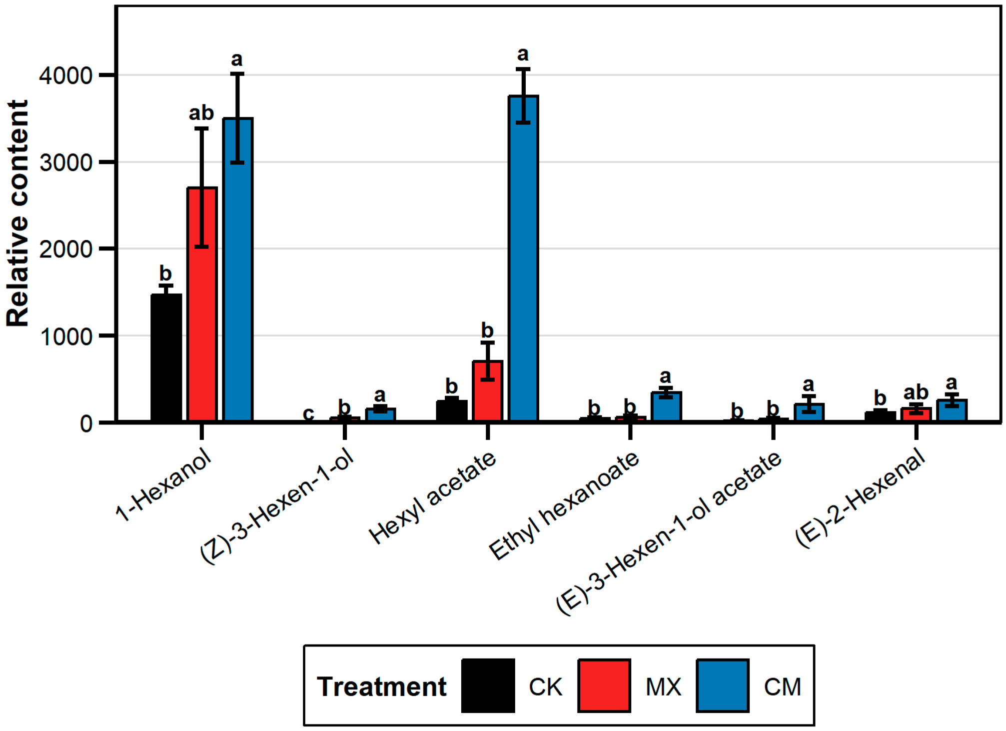

Figure 5. Effects of green manure treatments on characteristic aroma components of Korla fragrant pear during storage. Note: Different lowercase letters indicate significant differences at the same storage time point (Duncan's multiple range test, $p < 0.05$).

3.4. Effects of Green Manure Treatments on Soil Environment and Soil–Fruit Synergistic Effects

3.4.1. Effects of Green Manure Planting on Physicochemical Properties of Orchard Soil

As shown in Figure 6, green manure planting significantly altered the physicochemical properties of orchard soil. Regarding soil pH, the MX and CM treatments decreased by 0.11 and 0.12 units, respectively, compared with pre–planting levels ($p < 0.05$), whereas no significant change was observed in the CK treatment, indicating that green manure promoted soil acidification. Organic matter content was most significantly enhanced in the CM treatment, reaching an increase of 14.3% ($p < 0.05$), while the MX treatment showed an increase of 4.6%, and no significant change was observed in the CK treatment.

Soil nitrogen status exhibited marked divergence. Total nitrogen contents in the MX and CM treatments increased by 29.4% and 11.2%, respectively ($p < 0.05$), and alkali–hydrolyzable nitrogen showed a synchronous upward trend, with increases of 6.5% and 5.8%, respectively; nitrogen indicators in the CK treatment all decreased. Available phosphorus increased by 28.9% and 28.0% in the MX and CM treatments, respectively ($p < 0.05$), with no significant change in the CK treatment. Available potassium increased by 4.4% in the CM treatment, whereas no significant changes were observed in the MX and CK treatments, which is speculated to be related to the relatively high background potassium content in the soil of the study area.

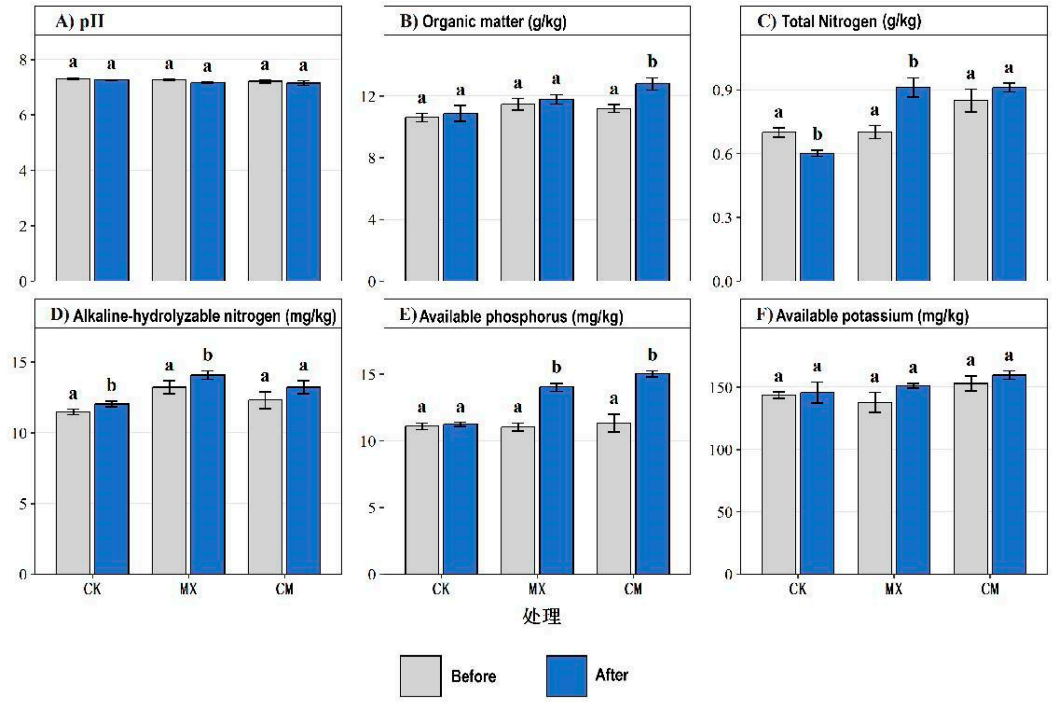

Figure 6. Effects of green manure planting on physicochemical properties of orchard soil. Note: Different lowercase letters indicate significant differences at the sameamong treatments (Duncan's multiple range test, $p <$ 0.05).

In summary, planting both MX (alfalfa) and CM (sweet clover) green manure could effectively improve orchard soil fertility. The CM treatment exhibited the optimal enhancement effect on organic matter, the MX treatment made the greatest contribution to nitrogen accumulation, and both green manure treatments exerted significant promoting effects on phosphorus activation.

3.4.2. Association Networks and Differential Mechanisms of Soil–Fruit Quality

The soil–fruit quality network constructed based on Pearson correlation (Figure 7) revealed obvious differences in network topological structure among different treatment groups. The network morphology of the control group (CK) was relatively loose, with 11 strongly correlated ($|r| \geq 0.8$) node pairs identified. Among these, available potassium occupied a central position, exhibiting highly positive correlations with organic acids and anthocyanins ($r = 0.976$ and $r = 0.955$, respectively); pH showed extensive negative correlations, particularly with organic acids reaching a correlation coefficient of –0.923. In contrast, the correlation of the organic matter node was relatively weak ($r = –0.018$ with organic acids).

The network structure of the MX treatment group changed significantly compared with CK. The number of strongly correlated connections in the network increased to 17, with total nitrogen and anthocyanins ($r = 0.999$), available potassium and anthocyanins ($r = 0.998$), and available phosphorus and organic acids all showing strong positive correlations. Notably, the relationship between the organic matter node and fruit quality indicators reversed from weak negative correlation in CK to strong positive correlation ($r = 0.982$). The CM treatment group exhibited different network characteristics. The proportion of negative correlations in this group increased to 64%, with directional reversal occurring in some key correlations. Specifically, the correlation coefficient between total nitrogen and vitamin C shifted from 0.809 in CK (via 0.093 in MX) to –0.997; a similar reversal occurred in the correlation between available potassium and anthocyanins.

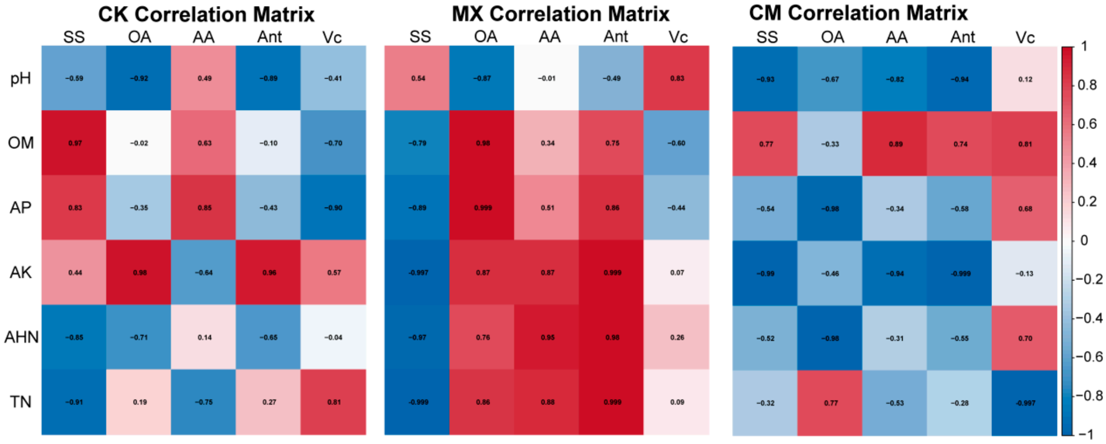

Figure 7. Correlation network of soil and fruit quality indicators under different treatments.

As shown in Figure 8, to further identify regulatory targets sensitive to management measures in the soil–fruit relationship, this study screened the five combinations with the largest coefficients of variation from all 30 indicator pairs for quantitative inter–group comparison.

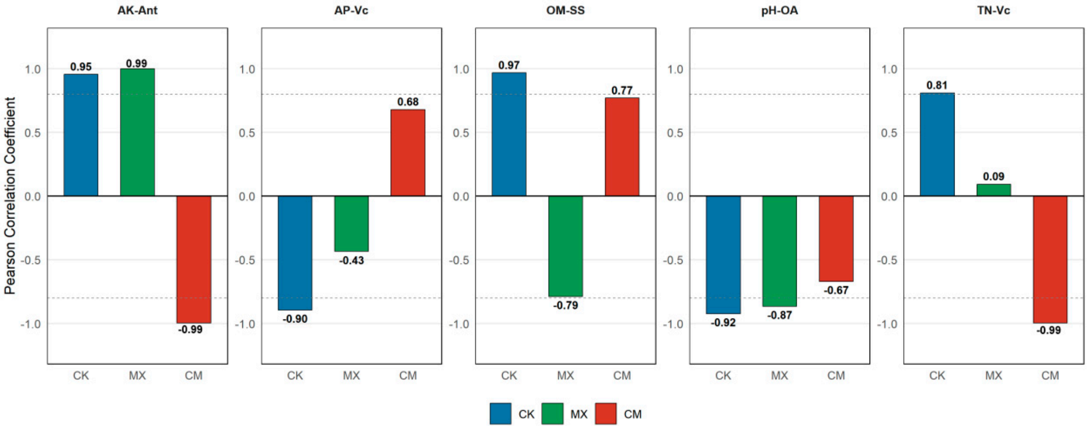

Figure 8. Differential comparison of key soil–fruit quality correlations among different treatments.

The association between available potassium and anthocyanins showed treatment sensitivity similar to that of the total nitrogen–vitamin C pair. In the CK group, the two showed a strong positive correlation (r = 0.955); the MX treatment strengthened this to an extremely strong positive correlation (r = 0.999), whereas the CM treatment reversed it to a completely negative correlation (r = –0.999). The correlation between pH and organic acids remained relatively stable across the three treatment groups, with correlation coefficients of –0.923, –0.866, and –0.670, respectively, and a variation amplitude of less than 7%. The relationship between organic matter and soluble sugars exhibited a fluctuation pattern of "positive–negative–positive," with correlation coefficients of 0.967, –0.788, and 0.769, respectively. The association between total nitrogen and vitamin C exhibited the most dramatic treatment sensitivity. The correlation coefficient attenuated from 0.809 in the CK group, through 0.093 in the MX group, to –0.997 in the CM group, with a magnitude of change reaching 1.806.

Integrating the results of Figure 7 and Figure 8, the two green manure treatments exhibited obviously different regulatory pathways on the soil–fruit association network. The MX treatment could enhance fruit anthocyanins and organic acids. The regulatory effects of the CM treatment on specific quality indicators were divergent, requiring comprehensive consideration in combination with production objectives.

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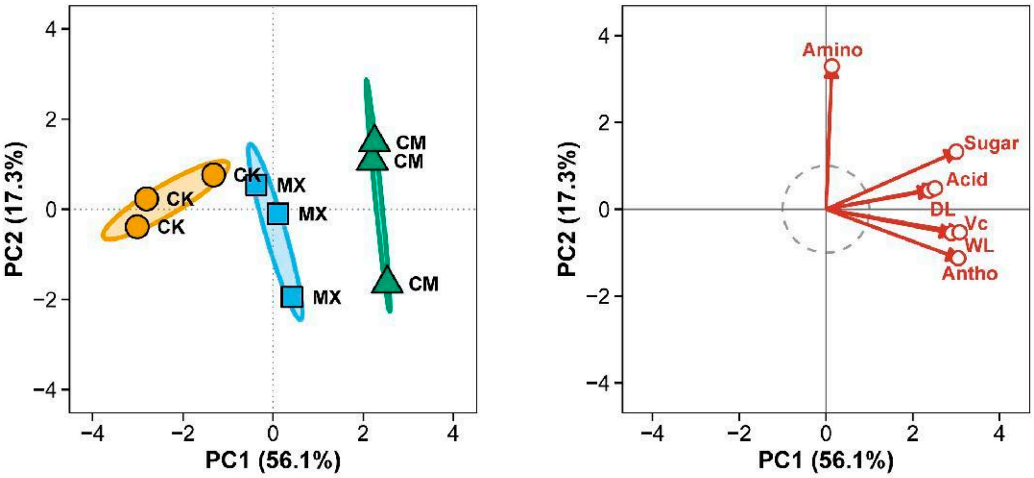
3.5. Correlation and Comprehensive Evaluation of Fruit Quality Indicators

As shown in Figure 9a, different treatments exhibited distinct spatial separation on the PC1–PC2 plane. CK (no–fertilizer control) was mainly distributed in the negative axis region of PC1, whereas the CM (sweet clover green manure) and MX (alfalfa green manure) treatments were oriented toward the positive axis direction of PC1, indicating that green manure application significantly altered the nutritional quality characteristics of the fruits. Among these, CM treatment samples clustered in the positive axis direction of PC2, while the MX treatment was relatively dispersed, suggesting that the sweet clover green manure treatment exhibited better consistency. Combined with the loading analysis in Figure 9b, the primary loading factors of PC1 were soluble sugars, organic acids, vitamin C, and anthocyanins, whereas PC2 primarily reflected the variation in amino acid content. The CM treatment showed positive correlations with soluble sugars, vitamin C, and anthocyanins, while the MX treatment was more strongly associated with amino acid accumulation. In summary, sweet clover green manure was conducive to enhancing the contents of soluble sugars, vitamin C, and anthocyanins in fragrant pear, whereas alfalfa green manure exerted a promoting effect on amino acid accumulation.



(**a**) (**b**)

Figure 9. Principal component analysis of nutritional quality of Korla fragrant pear fruits under different green manure treatments. (a) Score plot; (b) Loading plot. To clarify the overall effects of different green manure treatments on the nutritional quality of fragrant pear fruits, principal component analysis (PCA) was performed on seven key indicators. As shown in Figure 9, PC1 and PC2 cumulatively explained 73.4% of the variance, effectively reflecting the quality differences among samples.

3.6. Structural Equation Model of the Relationship Between Soil Properties and Fruit Quality

3.6.1. Model Specification and Sample Size Considerations

Partial least squares structural equation modeling (PLS–SEM) was conducted using SmartPLS 4 (v4.0, SmartPLS GmbH, Germany) (Ringle et al., 2024) to quantify the causal pathway from soil fertility to fruit quality under different green manure treatments. The structural model consisted of one exogenous latent variable, Soil Fertility (measured by AK, AN, AP, OM, and TN), and one endogenous latent variable, Fruit Quality (measured by AA, Anth, OA, SS, and Vc). Separate models were estimated for the CK, MX, and CM treatments, each with n = 10 observations.

The sample size of 10 observations per treatment meets the absolute minimum requirement for PLS–SEM according to the "10–times rule" (i.e., 10 observations per structural path [24];. However, it falls below the more conservative threshold of 50–100 observations recommended for models with five formative or reflective indicators per construct, and below the level required for stable bootstrapped standard errors. Consequently, all parameter estimates, significance tests, and model comparisons are presented as exploratory and descriptive, and should be interpreted with appropriate caution.

3.6.2. Measurement Model Assessment

3.6.3. Discriminant Validity

3.6.4. Structural Model Assessment

3.6.5. Model Fit Assessment

3.6.6. Results and Interpretation

As shown in Figure 10 and Table 3, the PLS–SEM results revealed a significant positive direct effect of Soil Fertility on Fruit Quality across all three green manure treatments, with distinct variations in path strength. In the control (CK), the standardized path coefficient (β) was 0.977 ($p < 0.001$), with an R^2 of 0.955, indicating that soil nutrient status explained 95.5% of the variance in fruit quality, confirming soil fertility as a core driving factor.

Regarding the outer loadings of soil indicators (Table 1; Figure 10), available potassium (AK, 0.862), available phosphorus (AP, 0.826), and alkali–hydrolyzable nitrogen (AN, 0.804) consistently exhibited high loadings (> 0.80) across all treatments, underscoring the dominant role of readily available nutrients in defining soil fertility. Notably, total nitrogen (TN) loaded weakly onto Soil Fertility in CK (0.438) but strongly in MX (0.991) and CM (0.753), suggesting that green manure incorporation enhanced the relevance of total nitrogen to the soil fertility construct.

Table 1. Measurement model results: outer loadings, composite reliability (CR), and average variance extracted (AVE).

Latent Variable	Indicator	CK	MX	CM	CR (CK/MX/CM)	AVE (CK/MX/CM)
Soil Fertility	AK	0.862	0.992	0.912	0.865 / 0.966 / 0.943	0.572 / 0.852 / 0.768
	AN	0.804	0.978	0.945		
	AP	0.826	0.974	0.946		
	OM	0.772	0.626	0.808		
	TN	0.438	0.991	0.753		
Fruit Quality	AA	0.749	0.841	0.939	0.935 / 0.959 / 0.941	0.744 / 0.825 / 0.763
	Anth	0.928	0.991	0.949		
	OA	0.932	0.941	0.884		
	SS	0.826	0.976	0.766		
	Vc	0.864	0.772	0.815		

Note: CR > 0.70 and AVE > 0.50 indicate satisfactory internal consistency and convergent validity. All outer loadings > 0.70 were retained, except TN in CK (0.438), which suggests a weaker contribution to the Soil Fertility construct under conventional management.

Green manure treatments significantly altered the soil–fruit quality pathway. The alfalfa (MX) treatment exhibited the strongest soil–to–quality transmission effect ($\beta = 0.985$, $p < 0.001$; $R^2 = 0.971$), with a path coefficient 0.8% higher than that of CK, indicating that alfalfa enhanced soil–fruit nutrient transfer efficiency through biological nitrogen fixation and root exudates. Conversely, the sweet clover (CM) treatment showed a markedly attenuated path coefficient ($\beta = 0.882$, $p = 0.003$; $R^2 = 0.777$), representing a 9.7% reduction compared to CK, suggesting that sweet clover may indirectly reduce the direct conversion efficiency of soil nutrients to fruit quality by altering the soil carbon–to–nitrogen ratio or root depth distribution.

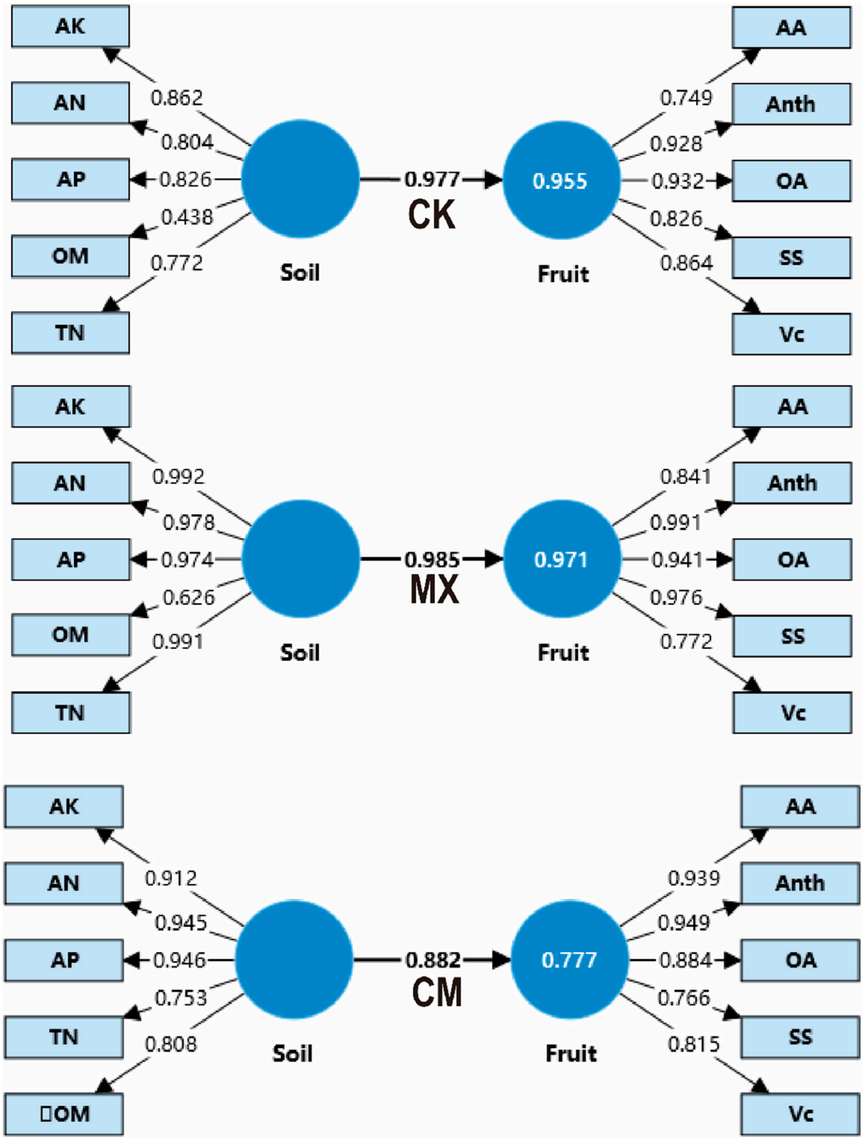


Figure 10. Path coefficients and factor loadings of the structural equation model for the effect of soil fertility on fruit quality under different green manure treatments.

For fruit quality indicators, organic acids (OA) and anthocyanins (Anth) displayed the highest and most stable loadings across all treatments (CK: 0.932/0.928; MX: 0.941/0.991; CM: 0.884/0.949), identifying them as robust proxies for the fruit quality latent variable. Notably, under the MX treatment, the loading of amino acids (AA) increased from 0.749 (CK) to 0.841, whereas vitamin C (Vc) showed a lower loading (0.772) compared to CK (0.864), suggesting differential contributions of functional nutritional components under alfalfa green manure.

Nevertheless, several measurement and model–fit limitations should be noted. All three treatments exhibited HTMT values exceeding the conservative threshold of 0.85 (Table 2), indicating that Soil Fertility and Fruit Quality were not fully empirically distinct—an outcome theoretically expected given their direct causal linkage but statistically problematic at $n = 10$. Furthermore, the SRMR values for CK (0.189) and CM (0.188) exceeded the 0.08 threshold (Table 4), suggesting that model fit was compromised in these treatments. Consequently, the comparative differences in R^2 and path coefficients among treatments should be treated as indicative patterns rather than definitive evidence of differential "soil–to–fruit transmission efficiency."

In summary, the PLS–SEM model quantitatively elucidated the causal pathway by which green manure application indirectly influences fruit quality through the regulation of soil fertility, with alfalfa green manure showing the optimal synergistic effect on soil and quality enhancement.

Table 2. Discriminant validity assessed by the Fornell–Larcker criterion and HTMT ratio.

Treatment	Latent Variable	Soil Fertility	Fruit Quality	HTMT
CK	Soil Fertility	0.756		1.108
	Fruit Quality	0.977	0.862	
MX	Soil Fertility	0.923		1.018
	Fruit Quality	0.985	0.908	
CM	Soil Fertility	0.877		0.925
	Fruit Quality	0.882	0.874	

Note: Bold diagonal values are the square roots of AVE. Off–diagonal values are Pearson correlations between latent variables. HTMT < 0.85 supports discriminant validity. All three treatments exhibited HTMT values exceeding the conservative threshold of 0.85, likely attributable to the small sample size (n = 10) and the strong theoretical linkage between soil fertility and fruit quality. These values should be interpreted with caution.

Table 3. Structural model results: path coefficients, explanatory power, effect sizes, and predictive relevance.

Path	β	SE	t	p	R^2	Adjusted R^2	f^2	Q^2
CK: Soil Fertility → Fruit Quality	0.977	0.215	4.538	< 0.001	0.955	0.949	21.084	0.665
MX: Soil Fertility → Fruit Quality	0.985	0.005	188.762	< 0.001	0.971	0.967	33.573	0.745
CM: Soil Fertility → Fruit Quality	0.882	0.3	2.94	0.003	0.777	0.749	3.491	0.477

Note: β = standardized path coefficient; SE = standard error from bootstrapping (5,000 subsamples, no sign changes); t = T statistic; p = two–tailed p–value; R^2 = coefficient of determination; f^2 = Cohen's effect size (0.02 = small, 0.15 = medium, 0.35 = large); Q^2 = Stone–Geisser predictive relevance ($Q^2 > 0$ indicates predictive accuracy). Owing to the small sample size (n = 10), bootstrapped standard errors may be underestimated and t–values inflated; therefore, the p–values and significance decisions are approximate and exploratory.

Table 4. Global model fit indices.

Fit Index	CK	MX	CM	Recommended Threshold	Interpretation
SRMR	0.189	0.077	0.188	< 0.08	MX: Good fit; CK/CM: Below threshold
d_ULS	1.973	0.33	1.948	< Bootstrap 95% CI	Exact fit not supported for CK/CM
d_G	n/a	n/a	n/a	< Bootstrap 95% CI	Not computable for saturated models

Note: SRMR = standardized root mean square residual; d_ULS = unweighted least squares discrepancy; d_G = geodesic discrepancy. Given the small sample size and model simplicity (one structural path), the SRMR values for CK and CM exceeded the conventional threshold of 0.08, suggesting that model fit is sensitive to sample size constraints. The MX model, however, achieved acceptable fit (SRMR = 0.077).

4. Discussion

4.1. Defining the Postharvest Quality Window

Our results show that Korla fragrant pear reaches a distinct quality window at 15 d of cold storage, when soluble sugars, organic acids, vitamin C, and anthocyanins peak simultaneously and the sugar–acid ratio settles between 131 and 138[25–27]. This pattern fits the general metabolic trajectory of climacteric fruit: starch hydrolysis continues to feed soluble sugar accumulation after the respiratory climacteric, while organic acid catabolism proceeds more slowly, creating a transient period of optimal balance [28]. What deserves attention is the 5–d delay in the sugar peak for CM (20 d versus 15 d for MX and CK), which indicates that green manure type can shift the timing of postharvest carbon mobilization by altering pre–harvest reserve status[26,29]. This moves the concept of harvest maturity beyond external colour and firmness to include an internal metabolic rhythm programmed by orchard soil management[20]. For practice, knowing the quality window for each green manure treatment allows growers to match green manure choice to market destination—immediate fresh consumption versus extended distribution chains—rather than relying on a single harvest standard[20,27].

4.2. Divergent Effects of CM and MX: From Soil Processes to Fruit Metabolism

The two green manures created clearly different domains of advantage. MX produced significantly higher fruit amino acid content than CM and CK, already evident on Day 1 of storage, which means the nitrogen benefit of alfalfa was transferred to fruit before harvest[30]. Alfalfa is a deep–rooted legume with strong biological nitrogen fixation; its residues decompose rapidly after incorporation and supply ample mineral nitrogen during the critical fruit development stage [6]. Nitrogen is the direct substrate for amino acid synthesis, and amino acids serve not only as protein building blocks but also as precursors for aroma volatiles and osmolytes [31]. This explains the superior nutritional quality under MX.

CM, in contrast, performed better in soluble sugars, characteristic ester volatiles, and anthocyanins. Sweet clover produces higher biomass and releases polyphenol–rich root exudates, traits that accelerate soil organic matter turnover and phosphorus mobilization [13,32]. In our study, CM increased soil organic matter by 14.3% and available phosphorus by 28.0%, both significantly higher than MX. Phosphorus is essential for glycolysis and photophosphorylation, and its abundant supply likely activated PEPC and related enzymes to drive soluble sugar accumulation [33]. while also promoting anthocyanin pigmentation through nutrient signaling [34]. More striking was the 14.4–fold increase in hexyl acetate under CM. Ester biosynthesis depends on acyl–CoA and alcohol precursors derived directly from sugar and lipid metabolism [35,36], and the carbon–rich rhizosphere environment under CM probably supplied more carbon skeletons for this pathway [37,38].

A contradiction emerges here: MX dominated in nitrogen supply yet fell behind CM in ester volatile production. The common assumption is that nitrogen promotes secondary metabolism, but our data point to a carbon–nitrogen trade–off. When nitrogen is abundant, carbon skeletons may be diverted preferentially into amino acid and protein synthesis, reducing the carbon flux available for volatile ester formation [39,40]. CM's relative nitrogen "restraint" may actually conserve carbon resources for ester synthesis. If this hypothesis holds, it carries a practical implication for orchard management: orchards targeting flavour quality should avoid excessive nitrogen, even from organic green manure sources[39].

4.3. Path Dependence in Soil–Fruit Linkages: Cross–Validation by PLS–SEM and Network Analysis

PLS–SEM revealed substantial differences in standardized path coefficients from soil fertility to fruit quality: 0.985 for MX, 0.977 for CK, and only 0.882 for CM [41]. This ranking does not follow the magnitude of soil fertility improvement—CM actually showed larger gains in organic matter and available phosphorus than MX. Better soil fertility does not automatically translate into better fruit quality; the conversion efficiency is regulated by green manure type.

The high path coefficient for MX likely stems from tight synchrony between nitrogen release and tree demand. Alfalfa residues have a low C/N ratio, decompose quickly, and release nitrogen that coincides with the fruit cell expansion phase, achieving a supply–demand match [42]. The attenuated coefficient for CM suggests a decoupling mechanism. One plausible explanation is C/N stoichiometric mismatch: sweet clover residues have a higher C/N ratio, and during early decomposition microbes compete with the tree for mineral nitrogen, creating a transient nitrogen deficit at a critical stage of fruit development [43] [42]. Although post–harvest soil tests showed increased total and alkali–hydrolyzable nitrogen under CM, much of this nitrogen may exist in organic forms with low immediate availability. The reversal of the total nitrogen–vitamin C correlation from +0.809 in CK to −0.997 in CM supports this interpretation—higher soil total nitrogen was associated with lower fruit vitamin C, indicating that this nitrogen pool was not effectively accessed by the tree.

Network topology analysis corroborates this view from another angle. In the CK network, available potassium occupied a central hub, reflecting the lingering dominance of chemical potassium fertilizer in conventionally managed orchards [44]. The MX network added strong positive links between organic matter and fruit quality, showing that alfalfa–derived carbon successfully entered the soil–fruit signalling pathway. The CM network, however, showed a surge in negative correlations (64%) and polarity reversals in key associations, indicating that sweet clover disturbed the existing soil–fruit equilibrium, possibly through allelochemical release or microbial community restructuring [45,46]. Taken together, green manure evaluation should not stop at soil nutrient content; the efficiency with which trees read and convert these nutrients into fruit quality matters just as much[47].

4.4. Practical Recommendations for Green Manure Selection in Orchards

These results argue against a one–size–fits–all approach to green manure [48,49]. For orchards prioritizing shelf–life extension and aroma intensity, CM is the better choice. For those targeting nutritional value (amino acids, vitamin C) and late–storage stability, MX is preferable[50]. Soil–fruit pathway efficiency (β and R^2) offers a new screening criterion to complement traditional soil fertility metrics[15]. The divergent quality windows also open possibilities for temporal precision marketing: MX fruit can be directed to early fresh markets, while CM fruit can enter channels requiring longer distribution cycles[20].

5. Conclusions

(1) This study identifies a postharvest quality window at 15 d of cold storage for Korla fragrant pear, when soluble sugars, organic acids, vitamin C, and anthocyanins peak concurrently and the sugar–acid ratio reaches an optimal range of 131–138.

(2) CM and MX exert markedly different regulatory effects on fruit quality. CM significantly increased soluble sugar content (32.54 mg/g at 20 d), anthocyanin content (44.41 mg/g), and characteristic ester volatiles (hexyl acetate increased 14.4–fold), producing a composite aroma with green, fruity, and sweet notes. MX significantly increased amino acid and vitamin C contents, and maintained a lower coefficient of variation for the sugar–acid ratio during late storage (3.4% versus 19.6% for CK).

(3) Soil fertility drives fruit quality positively, but the transmission efficiency depends on green manure type. MX showed the highest soil–to–fruit conversion efficiency (β = 0.985, R^2 = 0.970); CM showed lower efficiency (β = 0.882, R^2 = 0.778) than even CK (β = 0.977, R^2 = 0.955).

(4) Green manure type reshapes soil–fruit association patterns. MX strengthened positive correlations between organic matter and fruit quality indicators; CM caused polarity reversals in key associations such as total nitrogen–vitamin C and available potassium–anthocyanins, raising the proportion of negative correlations to 64%.

In summary, sweet clover and alfalfa influence postharvest quality of Korla fragrant pear through distinct soil–fruit coupling pathways. Alfalfa achieves higher nutrient transmission efficiency from soil to fruit, favouring nutritional quality and storage stability. Sweet clover promotes sugar accumulation and aroma compound synthesis, but with lower direct conversion efficiency from soil nutrients to fruit quality. Green manure selection in orchards should therefore be tailored to target quality traits.

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Institutional Review Board Statement: This study did not involve human or animal subjects. Field experiments on Korla fragrant pear were conducted in compliance with local agricultural regulations and institutional guidelines.

Informed Consent Statement: Not applicable

Data Availability Statement: The data presented in this study are available in the article. Raw data are available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

AA	Amino acids
AK	Available potassium
AN	Alkali–hydrolyzable nitrogen
ANOVA	Analysis of variance
Anth	Anthocyanins
AP	Available phosphorus
AVE	Average variance extracted
β	Standardized path coefficient
CK	Control
CM	Sweet clover (Melilotus officinalis)
CR	Composite reliability
CV	Coefficient of variation
DCIP	2,6–Dichlorophenolindophenol sodium salt

d_G	Geodesic discrepancy
d_ULS	Unweighted least squares discrepancy
EC	Electrical conductivity
EI	Electron ionization
f^2	Cohen's effect size
h°	Hue angle
HPLC	High–performance liquid chromatography
HPLC–UV	High–performance liquid chromatography with ultraviolet detection
HS–SPME–GC–MS	Headspace solid–phase microextraction coupled with gas chromatography–mass spectrometry
HTMT	Heterotrait–monotrait ratio
L*a*b*	CIE color space
m/z	Mass–to–charge ratio
MX	Alfalfa (Medicago sativa)
OA	Organic acids
OM	Organic matter
PCA	Principal component analysis
PITC	Phenyl isothiocyanate
PLS–SEM	Partial least squares structural equation modeling
Q^2	Stone–Geisser predictive relevance
R^2	Coefficient of determination
SD	Standard deviation
SE	Standard error
SRMR	Standardized root mean square residual
SS	Soluble sugars
TN	Total nitrogen
Vc	Vitamin C

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