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Enhancing Soil Physicochemical Properties and Fruit Production of *Rosa roxburghii* With Biochar-Based Fertilizer in Karst Agricultural Systems

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Keywords: biochar-based fertilizer | fruit quality | karst agriculture | *Rosa roxburghii* | soil amelioration | sustainable soil management

ABSTRACT

The development of sustainable agricultural practices in Karst regions faces significant challenges due to inherent soil limitations and complex terrain characteristics. This study investigated the effects of biochar-based fertilizers on soil properties and fruit quality of chestnut rose (*Rosa roxburghii)* in Southwest China's Karst region. Three biochar types derived from *R. roxburghii* pomace (RPB), discarded mushroom substrate (DMB), and chili straw (CSB) were evaluated at five application rates in combination with conventional fertilizers (with nitrogen, phosphorus, and potassium). Results revealed that the RPB4 treatment (70% biochar) significantly enhanced soil moisture content (61.37%), organic matter content (22.73%), and available nitrogen (22.74%) compared to controls. Fruit quality parameters showed significant improvements under optimal biochar treatments, with vitamin C content increasing by 67.94% (DMB4), total flavonoids by 120.06% (RPB4), and soluble sugars by 148.69% (RPB4). Structural equation modeling revealed significant direct effects of biochar application on soil water content (Standardized path coefficient = 0.60) and pH (0.80). Principal component analysis identified RPB4 as the optimal treatment combination, explaining 69.328% of total variance in soil and fruit properties. These findings provide quantitative evidence for the efficacy of biochar-based fertilizers in improving both soil quality and fruit characteristics in Karst agricultural systems, while establishing optimal application rates for sustainable orchard management.

Yangzhou Xiang and Jun Luo contributed equally to this work.

1 | Introduction

Sustainable agriculture has become a global priority in the face of challenges posed by soil degradation, climate change, and the need to balance productivity with ecological preservation (Basso and Antle 2020; Wang et al. 2022). In regions with fragile ecosystems, such as Karst landscapes, these challenges are particularly pronounced. Karst regions, covering approximately 7%–12% of the Earth's land surface, are characterized by their distinctive topography, porous limestone bedrock, and susceptibility to soil erosion (Fang et al. 2022). Poor soil fertility, water scarcity, and nutrient losses in these areas impose significant limitations on agricultural productivity and ecosystem services, necessitating innovative, site-specific solutions to ensure sustainable development.

Guizhou Province, located in southwestern China, exemplifies the complexities of agricultural production in Karst environments. More than 70% of its terrain is covered by Karst formations, where shallow, stony soils limit the growth of most crops (Bai et al. 2020). Within this challenging context, *Rosa roxburghii* Tratt has emerged as an economically significant crop species, distinguished by its exceptional nutritional profile, particularly its high vitamin C content, and growing presence in the health food sector (Liu et al. 2023; Xu et al. 2019). However, the intensification of *R. roxburghii* cultivation, coupled with reliance on traditional fertilization practices, particularly excessive nitrogen application, has led to severe soil degradation, reduced fruit quality, and declining yields (Wei et al. 2019). This degradation directly impacts both fruit yield and quality metrics, necessitating the development of alternative fertilization strategies that can simultaneously enhance productivity and preserve soil health.

Biochar-based fertilizers represent a promising strategy for addressing these dual challenges of farm productivity and soil health (Gong et al. 2025; Melo et al. 2022; Rombel et al. 2022). Biochar, derived from the pyrolysis of organic biomass under oxygen-limited conditions, has gained recognition for its multifunctionality in agricultural systems. Its porous structure and high cation exchange capacity allow it to improve soil water retention, pH regulation, and nutrient availability (González-Cencerrado et al. 2020; Joseph et al. 2021; Kapoor et al. 2022; Schmidt et al. 2021). Furthermore, the integration of biochar with chemical fertilizers has been shown to mitigate nitrogen losses, enhance soil organic matter content, and promote microbial activity, creating a favorable environment for plant growth (Bolans, et al. 2023; Feng et al. 2022; Omidvar et al. 2025; Zhang et al. 2021). However, existing studies have largely focused on annual crops or non-Karst soils, warranting further studies regarding the performance of biochar-based fertilizers in perennial orchards and complex terrains such as Karst regions.

R. roxburghii cultivation presents an ideal case for testing the potential of biochar-based fertilizers, given the crop's economic importance and the acute soil challenges in Guizhou's Karst areas (Dong et al. 2022; Luo et al. 2024; Xu et al. 2019). Previous research has found that balanced fertilization strategies, incorporating nitrogen, phosphorus, potassium, and calcium, can significantly improve *R. roxburghii* yield and quality (Wang and Fan 2017). Biochar, with its ability to modify soil structure and nutrient dynamics, offers an opportunity to address the specific needs of *R. roxburghii* cultivation while mitigating the adverse effects of excessive chemical fertilizer use (Chen et al. 2021).

Here, this study aimed to bridge these knowledge gaps by evaluating the effects of biochar-based fertilizers on the soil properties, yield, and fruit quality of *R. roxburghii* in Karst regions. Using biochar derived from locally available agricultural by-products, this study explored optimal nutrient formulations suited to the growth stages of *R. roxburghii*. Specifically, we intended to (1) quantify the impact of biochar-based fertilizers on soil physicochemical properties, such as pH, organic matter, and nutrient content; (2) assess changes in yield and key fruit quality indicators, including vitamin C and flavonoid content; and (3) identify the most effective biochar-based fertilizer formulations through principal component analysis and structural equation modeling. The findings of this study not only contribute to the sustainable management of *R. roxburghii* orchards in Guizhou but also provide a replicable model for integrating biochar-based fertilizers into other Karst agricultural systems globally.

2 | Materials and Methods

2.1 | Experimental Site

The study was conducted in Chaxiang Village, Gujiao Town, Longli County, Guizhou Province, China (106°42′–107°17′ E, 26°15′–26°56′ N). This region is characterized by a subtropical monsoon humid climate with a mean annual temperature of 13.2°C and an average annual precipitation of approximately 1100 mm. The area experiences 1060–1265 h of annual sunshine, and the frost-free period extends up to 283 days. The Karst landscape features typical peak-cluster depressions, with altitudes ranging from 1100–1200 m. The predominant soil type is yellow soil, with a pH of 5.87, organic matter content of 33.91 $g\,kg^{-1}$, and available nutrients including alkaline hydrolysable nitrogen (56.28 $mg\,kg^{-1}$), phosphorus (39.83 $mg\,kg^{-1}$), and potassium (109.37 $mg\,kg^{-1}$). The fertility of the soil was so fertile, not poor as you mentioned in the INTRO, if your description in the MM section were correct.

2.2 | Biochar Production and Characterization

2.2.1 | Raw Material Selection and Preparation

Raw materials were sourced from local agricultural by-products in Longli County, comprising *R. roxburghii* pomace from the processing facility in Chaxiang Village, discarded mushroom cultivation substrate from Yuanbao Village, and *Capsicum annuum* (chili) straw from Guoli Village's cultivation base.

2.2.2 | Biochar Production Method

The production process followed the following sequential steps: (1) pre-treatment, raw materials were thoroughly washed with deionized water to remove impurities and soluble salts; materials were oven-dried at 105°C for 24 h to achieve constant weight, and dried materials were ground and sieved through a 2mm mesh; (2) ground materials were placed in a programmable muffle furnace under a continuous flow of high-purity nitrogen (N_2, 99.99%) at 1 L min^{-1} to ensure an oxygen-limited atmosphere. The furnace temperature was increased at a rate of 5°C per minute until reaching the peak temperature of 350°C and was held for 2h. Afterward, the samples were allowed to cool naturally to ambient temperature under the continuous N_2 atmosphere; (3) post-production processing, resultant biochar was ground to pass through a 2mm sieve, and materials were stored in sealed containers until use. Eventually, three biochar types were produced: *R. roxburghii* pomace biochar (RPB), discarded mushroom-stick biochar (DMB), and chili straw biochar (CSB) (Table 1).

TABLE 1 | Physicochemical properties of three biochar types: *R. roxburghii* pomace biochar (RPB), discarded mushroom-stick biochar (DMB), and chili straw biochar (CSB).

Property	RPB	DMB	CSB
pH	9.2–10.1	8.5–9.3	8.8–9.5
Electrical conductivity (mS cm^{-1})	2.8–3.2	1.5–2.0	2.0–2.5
Total carbon (%)	68–72	62–67	58–63
Total nitrogen (%)	0.8–1.2	1.2–1.6	1.0–1.4
Total phosphorus (%)	0.31–0.52	0.31–0.42	0.22–0.43
Total potassium (%)	1.8–2.2	1.2–1.6	2.0–2.4
Porosity (%)	65–75	55–65	60–70
CEC (cmol kg^{-1})	15.1–18.0	12.4–15.1	13.4–16.2

2.3 | Fertilizer Formulation and Treatment Design

2.3.1 | Chemical Fertilizer Components

The study utilized the following three kinds of fertilizers (Table 2): urea (N 46%), calcium superphosphate (P_2O_5 12%), and potassium sulfate (K_2O 52%).

2.3.2 | Biochar-Based Fertilizer Preparation

Sixteen treatment combinations were formulated, incorporating varying ratios of biochar and conventional fertilizers (Table 2). The fertilizer combinations were designed to address three critical growth stages: base fertilization (pre-growing season), fruit set fertilization, and fruit swelling fertilization. Treatment ratios were calculated based on established nutrient requirements for *R. roxburghii* at different phenological stages, with biochar incorporation rates ranging from 40% to 80% of the total mixture mass (Liu et al. 2023; Wang and Fan 2017).

TABLE 2 | Composition ratios of biochar-based fertilizer treatments applied to *R. roxburghii* orchards.

	Base fertilizer (%)				Fruit set fertilizer (%)				Fruit swelling fertilizer (%)			
Treatments	Biochar	N	P	K	Biochar	N	P	K	Biochar	N	P	K
Control	0	0	0	0	0	0	0	0	0	0	0	0
RPB1	40	30	20	10	40	20	20	20	40	20	15	25
RPB2	50	25	15	10	50	17	17	16	50	17	13	20
RPB3	60	20	12	8	60	14	13	13	60	13	10	17
RPB4	70	15	8	7	70	10	10	10	70	9	7	14
RPB5	80	10	6	4	80	7	7	6	80	6	5	9
DMB1	40	30	20	10	40	20	20	20	40	20	15	25
DMB2	50	25	15	10	50	17	17	16	50	17	13	20
DMB3	60	20	12	8	60	14	13	13	60	13	10	17
DMB4	70	15	8	7	70	10	10	10	70	9	7	14
DMB5	80	10	6	4	80	7	7	6	80	6	5	9
CSB1	40	30	20	10	40	20	20	20	40	20	15	25
CSB2	50	25	15	10	50	17	17	16	50	17	13	20
CSB3	60	20	12	8	60	14	13	13	60	13	10	17
CSB4	70	15	8	7	70	10	10	10	70	9	7	14
CSB5	80	10	6	4	80	7	7	6	80	6	5	9

Note: Treatments include three biochar types (CSB, chili straw biochar; DMB, discarded mushroom substrate biochar; RPB, *R. roxburghii* pomace biochar) combined with conventional nitrogen (N), phosphorus (P), and potassium (K) fertilizers at five application rates. Values represent percentage composition by mass for each fertilizer component during base fertilization, fruit set, and fruit swelling stages ($n = 3$).

2.4 | Field Experimental Design and Orchard Management

2.4.1 | Experimental Layout

A field experiment was conducted using 10-year-old *R. roxburghii* plants. The treatments were randomly assigned within each of three blocks, with each block containing all 16 treatments to account for potential site heterogeneity. Plot dimensions (8 m × 3 m) and spacing between plots (6 m) ensured adequate buffer zones to prevent treatment interference. Each plot contained 10 *R. roxburghii* plants. Fifteen of the treatments involved biochar-based fertilizer combinations (five different fertilizer combinations per biochar source), and one treatment served as a control (e.g., either a conventional fertilizer or no amendment).

Standard orchard management practices were applied uniformly across all treatments. These practices included pruning, weed control through manual removal, integrated pest management, and irrigation. Pruning was conducted once a year to remove dead or diseased branches, while weed control was performed as needed to minimize competition. Pest management relied on locally recommended measures, including regular scouting and the use of approved pesticides only when pest thresholds were exceeded.

Irrigation decisions were based on soil moisture monitoring. Soil moisture was checked at regular intervals (e.g., weekly or biweekly) using a time-domain reflectometer (TDR) probe. When soil moisture fell below a predetermined threshold (e.g., 70% of field capacity), supplemental irrigation was provided to restore adequate moisture for plant growth.

2.4.2 | Fertilizer Application Method

Fertilizers were applied by digging trenches along the canopy drip line of each plant at three key phenological stages: (1) base fertilizer application: 3.0 kg per plant; (2) fruit set application: 2.0 kg per plant; (3) fruit swelling application: 1.5 kg per plant.

Each of the 15 biochar-based fertilizer treatments was applied according to one of the biochar-fertilizer combinations, while the control treatment followed the same trench-application method without biochar or fertilizer regime (Table 2).

2.5 | Sampling and Analytical Methods

2.5.1 | Soil Sampling Protocol

Soil samples were collected during the fruit maturation stage. Five sampling points were established in each plot, located 10 cm inside and outside the canopy's vertical projection. Soil samples were collected from a depth of 0–20 cm, mixed, and stored in sealed bags. Samples were air-dried, sieved through a 1 mm mesh, and analyzed for pH, organic matter, total and available nitrogen, phosphorus, and potassium.

2.5.2 | Fruit Sampling and Yield Assessment

Fruit sampling followed a standardized protocol. 1 kg fresh fruit samples were collected from 5 representative trees per plot; samples were immediately stored in ice-cooled containers and transported to laboratory facilities within 2 h of collection. Remaining fruits were harvested and weighed for yield determination.

2.5.3 | Analytical Methods of Soil Physicochemical Properties

Soil physicochemical analysis was conducted according to the methods outlined in Soil agrochemical analysis (Third edition) (Bao 2008): soil moisture content (MC) was determined using the oven-drying method; pH was measured with a pH meter (water/soil ratio of 2.5:1); soil organic matter (SOM) was determined by the dichromate potassium volumetric with external heating method; total nitrogen (TN) was measured using the Kjeldahl method; total phosphorus (TP) was assayed by sodium hydroxide fusion, molybdenum antimony heteropoly acid colorimetric method; total potassium (TK) was determined by sodium hydroxide fusion, flame photometry method; available nitrogen (AN) was assayed using the alkali hydrolysis diffusion method; available phosphorus (AP) was measured by sodium bicarbonate extraction, molybdenum antimony heteropoly acid colorimetric method; available potassium (AK) was determined by ammonium acetate extraction, flame photometry method.

2.5.4 | Analytical Methods of *R. roxburghii* Fruit Quality

The external quality of the fruit was primarily assessed for single fruit weight, transverse diameter, and longitudinal diameter, with the single fruit weight being determined using an electronic balance (accuracy of 0.01 g); the transverse and longitudinal diameters were measured with a vernier caliper (accuracy of 0.01 mm). The internal quality of the fruit mainly involved the determination of fruit water content, Vitamin C, total flavonoids, soluble sugar content, and titratable acidity, with the fruit water content being measured using the oven-drying method; Vitamin C content was determined using the ammonium sulfate-molybdate method (Song et al. 2020). Total flavonoid content was assayed by the aluminum nitrate-sodium nitrite method (Luo et al. 2024). Soluble sugar content was measured using the anthrone colorimetry method (Kou et al. 2023). Titratable acidity content was determined by NaOH (pH 13.0, 0.1 mol L^{-1}) titration method (Dong et al. 2022).

2.6 | Statistical Analysis

Initial data organization and validation were performed using Microsoft Excel 2016. Treatment effects on soil physicochemical properties and *R. roxburghii* fruit parameters were evaluated through one-way analysis of variance (ANOVA) using SPSS version 26.0. The normality and homoscedasticity of residuals were verified using Shapiro–Wilk and Levene's tests, respectively. Post hoc comparisons between treatment means employed Fisher's least significant difference (LSD) test at $\alpha = 0.05$.

Graphical representations were generated using OriginPro 2024, with error bars representing standard deviations of means.

Principal Component Analysis (PCA) was employed to identify optimal biochar-based fertilizer formulations through dimensionality reduction of the multivariate response data. This approach transforms potentially correlated variables into orthogonal principal components that capture maximum variance in the dataset (Abdi and Williams 2010). Prior to analysis, all variables were standardized to zero mean and unit variance to account for differing measurement scales. The analysis incorporated 17 response variables encompassing soil physicochemical properties, yield components, and fruit quality parameters. Principal components were extracted based on eigenvalues > 1.0, with varimax rotation applied to optimize component loading patterns.

The original data of soil and fruit indicators in the *R. roxburghii* orchard were standardized, and the scores of the first and second principal components were calculated based on the standardized indicators and the factor loading matrix, as shown in Equations (1) and (2) respectively. Based on the results of the principal component analysis, a weighted sum was conducted using the relative contribution rates of the variance corresponding to the two principal components as weights. The comprehensive ranking of the 16 experimental treatments for 17 soil and fruit indicators was determined.

$$\begin{aligned} \mathrm{F1} = {} & 0.013X_1 + 0.092X_2 + 0.129X_3 + 0.007X_4 + 0.044X_5 - \\ & 0.022X_6 + 0.033X_7 - 0.090X_8 + 0.138X_9 - 0.033X_{10} - \\ & 0.011X_{11} + 0.041X_{12} + 0.052X_{13} + 0.086X_{14} + 0.051X_{15} + \\ & 0.102X_{16} + 0.081X_{17} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{F2} = {} & 0.080X_1 - 0.006X_2 - 0.062X_3 + 0.080X_4 + 0.050X_5 + \\ & 0.099X_6 + 0.054X_7 + 0.160X_8 - 0.070X_9 + 0.115X_{10} + \\ & 0.099X_{11} + 0.054X_{12} + 0.031X_{13} + 0.004X_{14} + 0.040X_{15} - \\ & 0.013X_{16} - 0.016X_{17} \end{aligned} \tag{2}$$

Mantel tests were performed using the "*vegan*" package to assess the correlations between variable matrices, with edge widths in the network visualization representing Mantel's *r* values. The statistical significance of these correlations was indicated through edge colors, while Pearson's correlation coefficients were employed to quantify pairwise relationships between variables (Oksanen et al. 2013). Linear regression analyses were subsequently implemented to evaluate the specific effects of biochar application rates on yield indices (fruit yield, single fruit weight, fruit diameter, and fruit length) and quality parameters (vitamin C content, total flavonoids, soluble sugar, and titratable acid). The regression models incorporated soil moisture content and an integrated fertilizer score, calculated by standardizing and averaging nitrogen (N), phosphorus (P), and potassium (K) fertilizers application rates. Statistical significance was assessed through regression coefficients (R^2) and *p*-values.

Structural Equation Modeling (SEM) was implemented to elucidate causal pathways between biochar application, soil properties, and fruit characteristics using R version 4.2.1 with the "*lavaan*" package (Rosseel 2012). The initial theoretical model incorporated nine soil parameters (moisture, pH, organic matter, total and available forms of nitrogen phosphorus, and potassium) and eight fruit quality metrics (yield, weight, dimensions, and biochemical constituents) as measured variables. Model evaluation employed multiple fit indices (Liu et al. 2024): Chi-squared test (χ^2) with degrees of freedom ratio (χ^2/df < 3.0), comparative fit index (CFI > 0.95), root mean square error of approximation (RMSEA < 0.08), and standardized root mean square residual (SRMR < 0.08). Model refinement proceeded iteratively, with modification indices guiding the addition of significant paths ($p < 0.05$) while maintaining theoretical consistency.

3 | Results

3.1 | Effects of Biochar-Based Fertilizer on Soil Physicochemical Properties

Application of biochar-based fertilizers significantly influenced soil physicochemical properties in the *R. roxburghii* orchard system (Figure 1). The most pronounced effects were observed in soil moisture content (Figure 1a), pH change (Figure 1b), and nutrient availability dynamics. Soil moisture content showed significant enhancement under biochar treatments, with the highest retention observed in the RPB4 treatment (31.18%), representing a 61.37% increase relative to control conditions ($p < 0.05$, Figure 1c). The DMB4 and CSB5 treatments similarly indicated substantial improvements, achieving 27.84% and 27.50% moisture content, respectively. Soil pH showed treatment-dependent responses, with RPB5, DMB5, and CSB5 treatments elevating pH to 7.01, 6.99, and 6.92, respectively. This represents significant increases of 19.50%, 19.27%, and 18.08% above control treatment.

Organic matter content showed significant enhancement under biochar amendment, with the RPB4, DMB4, and CSB3 treatments achieving concentrations of 42.44, 43.43, and 44.29 g kg^{-1}, respectively (Figure 1c). These values represent increases of 22.73%, 25.57%, and 28.08% above control treatments ($p < 0.05$). Nitrogen dynamics suggested complex responses to treatment applications (Figure 1d,e). TN content reached maximum values under RPB3 treatment (1.35 g kg^{-1}), while AN showed optimal response to RPB4 treatment (69.41 mg kg^{-1}). These changes represent increases of 17.43% and 22.74%, respectively, relative to control treatment ($p < 0.05$). Phosphorus availability showed similar treatment-dependent enhancement (Figure 1f,g). TP content peaked under RPB5 treatment (1.07 g kg^{-1}), while AP showed the maximum response to RPB4 treatment (46.75 mg kg^{-1}). These improvements represent increases of 25.50% and 17.42%, respectively, compared to control treatment ($p < 0.05$). Potassium dynamics showed significant changes under biochar amendment (Figure 1h,i). TK content achieved the maximum values under RPB5 treatment (37.74 g kg^{-1}), while AK peaked under DMB5 treatment (147.81 mg kg^{-1}). These enhancements represent increases of 25.34% and 34.52%, respectively, above control treatment ($p < 0.05$).

3.2 | Effects of Biochar-Based Fertilizer on Fruit Yield and Quality Parameters

Biochar-based fertilizer applications significantly influenced both yield components and external fruit characteristics of *R.*

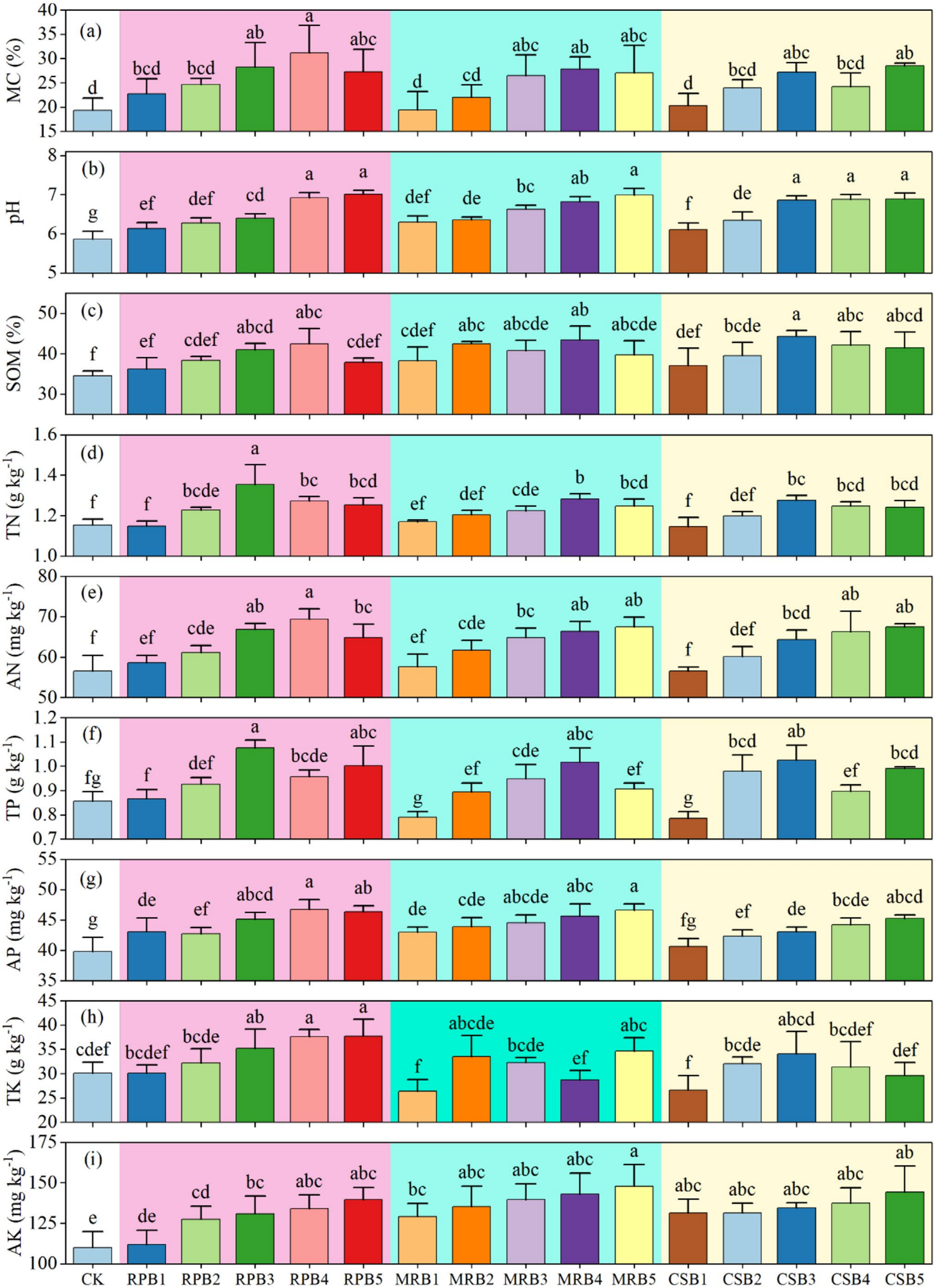

FIGURE 1 | Legend on next page.

FIGURE 1 | Effects of biochar-based fertilizer treatments on soil physicochemical properties in *R. roxburghii* orchards. (a) Soil moisture content; (b) pH; (c) organic matter; (d) total nitrogen; (e) available nitrogen; (f) total phosphorus; (g) available phosphorus; (h) total potassium; (i) available potassium. Data points represent means ± standard deviation ($n = 3$). Different letters indicate significant differences between treatments at $p < 0.05$. CSB, chili straw biochar; DMB, discarded mushroom substrate biochar; RPB, *R. roxburghii* pomace biochar; numbers 1–5 indicate increasing biochar ratios (Table 2).

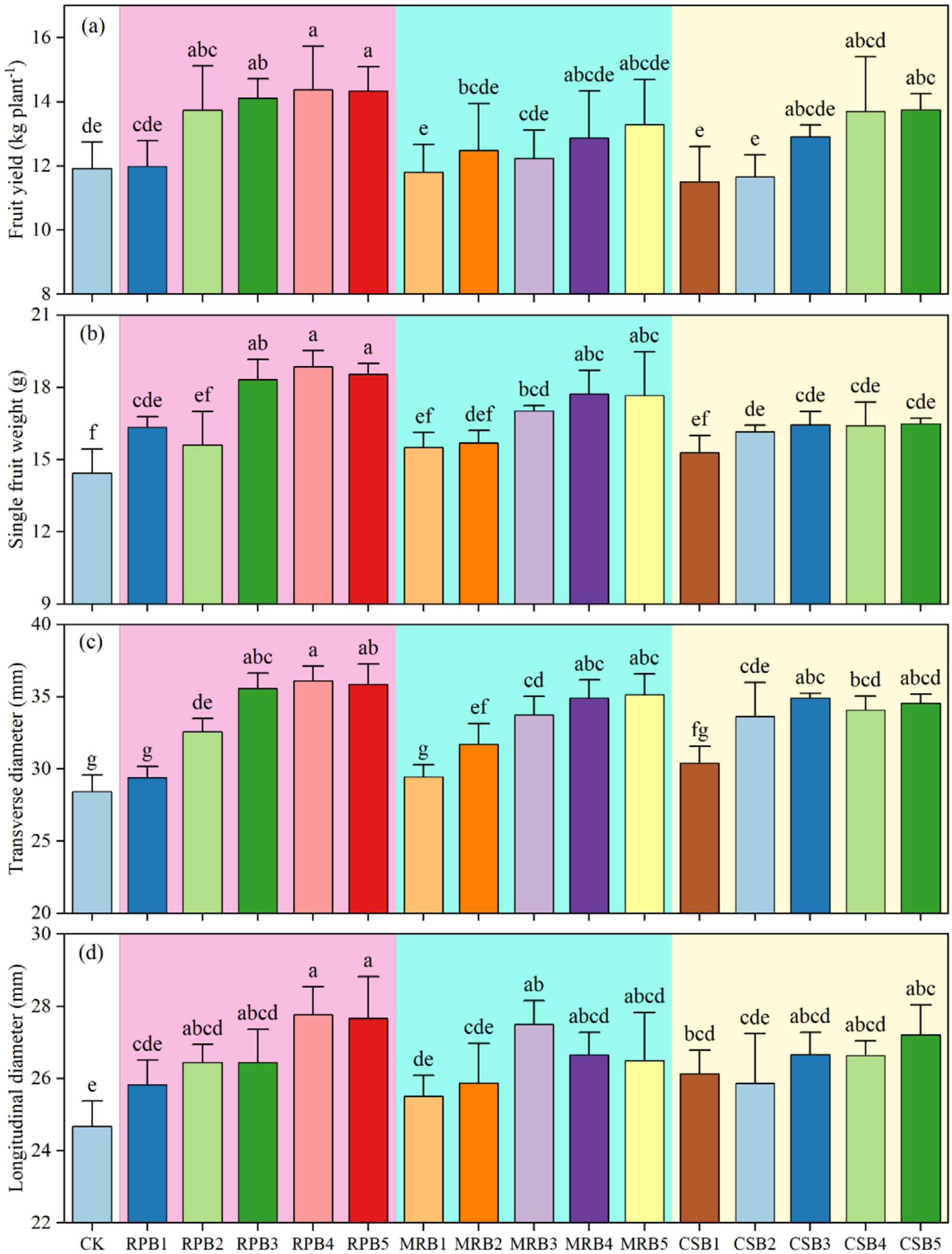

FIGURE 2 | Impact of biochar-based fertilizer treatments on *R. roxburghii* fruit yield components and external characteristics. (a) Yield per plant; (b) single fruit weight; (c) transverse diameter; (d) longitudinal diameter. Values represent means ± standard deviation ($n = 3$). Different letters indicate significant differences between treatments at $p < 0.05$. Treatment abbreviations as in Table 1.

roxburghii (Figure 2). Fruit yield showed significant enhancement under RPB4 treatment (Figure 2a), achieving 14.37 kg plant^{-1} and representing a 20.59% increase above control values ($p < 0.05$). The DMB5 and CSB5 treatments similarly showed substantial yield improvements, reaching 13.28 and 13.75 kg plant^{-1} respectively.

Individual fruit weight showed significant response to treatment application (Figure 2b), with RPB4 treatment achieving the maximum value of 18.86 g, representing a 30.59% increase relative to control treatment ($p < 0.05$). Fruit dimensional analysis revealed significant enhancement in both transverse and longitudinal diameters, with maximum values observed

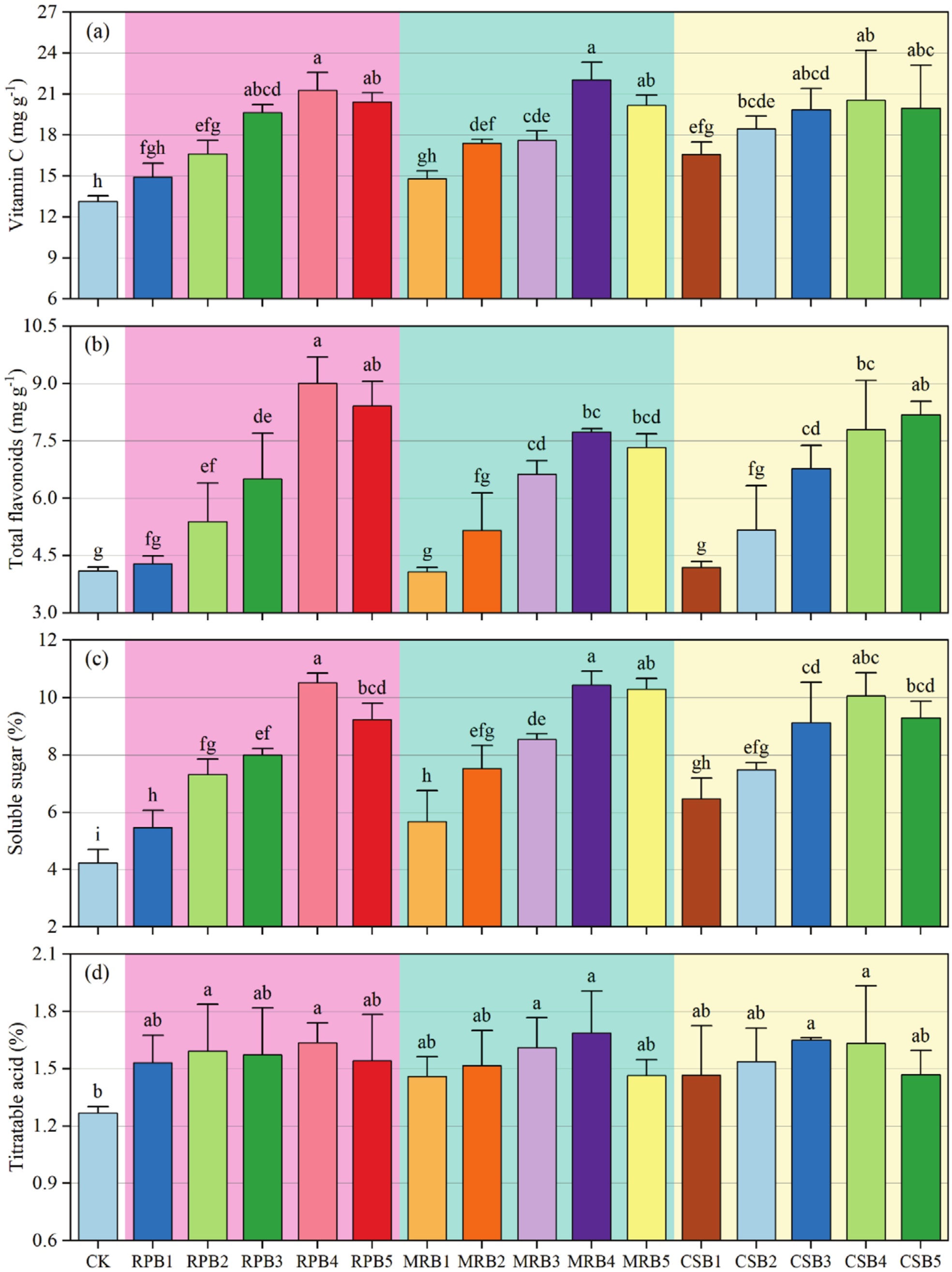

FIGURE 3 | Changes in *R. roxburghii* fruit quality parameters under biochar-based fertilizer treatments. (a) Vitamin C content; (b) total flavonoids; (c) soluble sugar content; (d) titratable acidity. Data points represent means ± standard deviation ($n = 3$). Different letters indicate significant differences between treatments at $p < 0.05$. Treatment abbreviations as in Table 2.

under RPB4 treatment (36.11 mm and 27.77 mm respectively, Figure 2c,d).

3.3 | Changes to Internal Fruit Quality Parameters

Internal fruit quality parameters showed significant responses to biochar-based fertilizer applications (Figure 3). Vitamin C content demonstrated treatment-dependent enhancements (Figure 3a), with maximum values observed under DMB4 treatment (22.04 $mg\,g^{-1}$), representing a 67.94% increase above control ($p < 0.05$). Total flavonoid content showed similar improvements (Figure 3b), reaching the maximum value under RPB4 treatment (9.00 $mg\,g^{-1}$), representing a 120.06% increase relative to control treatment.

Soluble sugar content exhibited significant enhancement under RPB4 treatment (Figure 3c), achieving 10.52% concentration and representing a 148.69% increase above control values ($p < 0.05$). Titratable acidity showed optimal response under DMB4 treatment (Figure 3d), reaching 1.69% and representing a 33.14% increase relative to control treatment.

3.4 | Principal Component, Structural Equation Analysis, and Comprehensive Evaluation

Principal component analysis revealed three significant components (eigenvalues >1) explaining 81.73% of total variance (Table 3). The first principal component (eigenvalue = 14.56) explained 69.33% of variance, with major loadings from available potassium (0.138), organic matter (0.13), and soluble sugar content (0.10). The second principal component (eigenvalue = 3.34) explained an additional 15.88% of variance, primarily influenced by total potassium (0.16) and yield parameters (0.12).

Principal component analysis of the 17 soil and fruit quality parameters revealed a hierarchical efficacy pattern among treatments, with RPB4 demonstrating superior performance (comprehensive score: 1.73), followed by RPB5 (1.25) and DMB4 (1.10). Sequential ranking of treatments exhibited a clear gradient of declining efficacy: RPB4 > RPB5 > DMB4 > RPB3 > DMB5 > CSB5 > CSB3 > CSB4 > DMB3 > RPB2 > DMB2 > CSB2 > RPB1 > DMB1 > CSB1 > CK (Table 4). Optimal amelioration of soil properties and enhancement of fruit quality parameters were achieved with the RPB4 treatment, comprising *R. roxburghii* pomace biochar, nitrogen, phosphorus, and potassium at mass ratios of 4.55:0.79:0.55:0.62 kg, respectively (Table 2).

TABLE 3 | Principal component analysis of soil physicochemical properties and fruit quality parameters under biochar-based fertilizer treatments.

Index	PC1	PC2
SMC	0.013	0.080
pH	0.092	−0.006
SOM	0.129	−0.062
TN	0.007	0.080
AN	0.044	0.050
TP	−0.022	0.099
AP	0.033	0.054
TK	−0.090	0.160
AK	0.138	−0.070
Yield	−0.033	0.115
SFW	−0.011	0.099
FD	0.041	0.054
FL	0.052	0.031
Vitamin C	0.086	0.004
Total flavonoids	0.051	0.040
Soluble sugar	0.102	−0.013
Titratable acid	0.081	−0.016
Eigenvalue	14.559	3.335
Variance contribution rate (%)	69.328	15.881
Cumulative contribution rate (%)	69.328	85.208

Note: Values represent component loadings, eigenvalues, and variance contribution rates for factors explaining > 85% of total variance.

TABLE 4 | Comprehensive evaluation scores of different biochar-based fertilizer treatments based on weighted principal component analysis.

Treatments	F_1-score	F_2-score	Total score	Rank
CK	−1.6196	−0.7600	−2.3797	16
RPB1	−0.9637	−0.4373	−1.4010	13
RPB2	−0.3780	−0.0048	−0.3829	10
RPB3	−0.0034	0.9736	0.9702	4
RPB4	0.6480	1.0781	1.7261	1
RPB5	0.2640	0.9819	1.2459	2
DMB1	−0.5560	−1.0274	−1.5835	14
DMB2	−0.1223	−0.3537	−0.4760	11
DMB3	0.3295	0.0279	0.3574	9
DMB4	0.9393	0.1608	1.1001	3
DMB5	0.5028	0.3770	0.8798	5
CSB1	−0.5017	−1.1045	−1.6062	15
CSB2	−0.2233	−0.2695	−0.4928	12
CSB3	0.4704	0.2348	0.7051	7
CSB4	0.6011	0.0110	0.6122	8
CSB5	0.6129	0.1121	0.7250	6

Note: Scores incorporate soil improvement indices, yield parameters, and fruit quality metrics. Values represent mean scores ± standard deviation ($n = 3$). Different letters indicate significant differences at $p < 0.05$ (LSD test).

The Mantel test indicated significant correlations between biochar application rates and fruit yield indices and quality indices (Figure 4). Specifically, biochar application showed positive associations with soil nutrient availability ($p < 0.05$). Network analysis indicated that chemical fertilizer applications exhibited stronger correlations with yield and titratable acidity content compared to biochar treatments.

Two SEM models were constructed to analyze treatment effects on yield (Figure 5a) and quality parameters (Figure 5b), respectively. Biochar application exhibited significant positive direct effects on both yield ($\beta = 0.60$, $p < 0.001$, Figure 5a) and quality parameters (0.54, $p < 0.001$, Figure 5b). These beneficial effects were partially counteracted by conventional fertilizer applications (control treatment), which suggested modest negative influences on yield (−0.14, $p < 0.05$) and quality metrics (−0.16, $p < 0.05$). Analysis of soil parameter changes revealed that biochar application significantly enhanced soil water content ($\beta = 0.60$, $p < 0.001$), pH (0.80, $p < 0.001$), and mineral nutrient status (0.69, $p < 0.001$). Conventional fertilizer applications exhibited an antagonistic effect on soil pH (−0.25, $p < 0.001$), suggesting potential acidification processes. Soil moisture content emerged as a significant mediator of yield responses (0.42, $p < 0.001$), while soil organic matter showed selective influence on fruit quality parameters (0.07, $p < 0.05$) despite showing no significant response to biochar application.

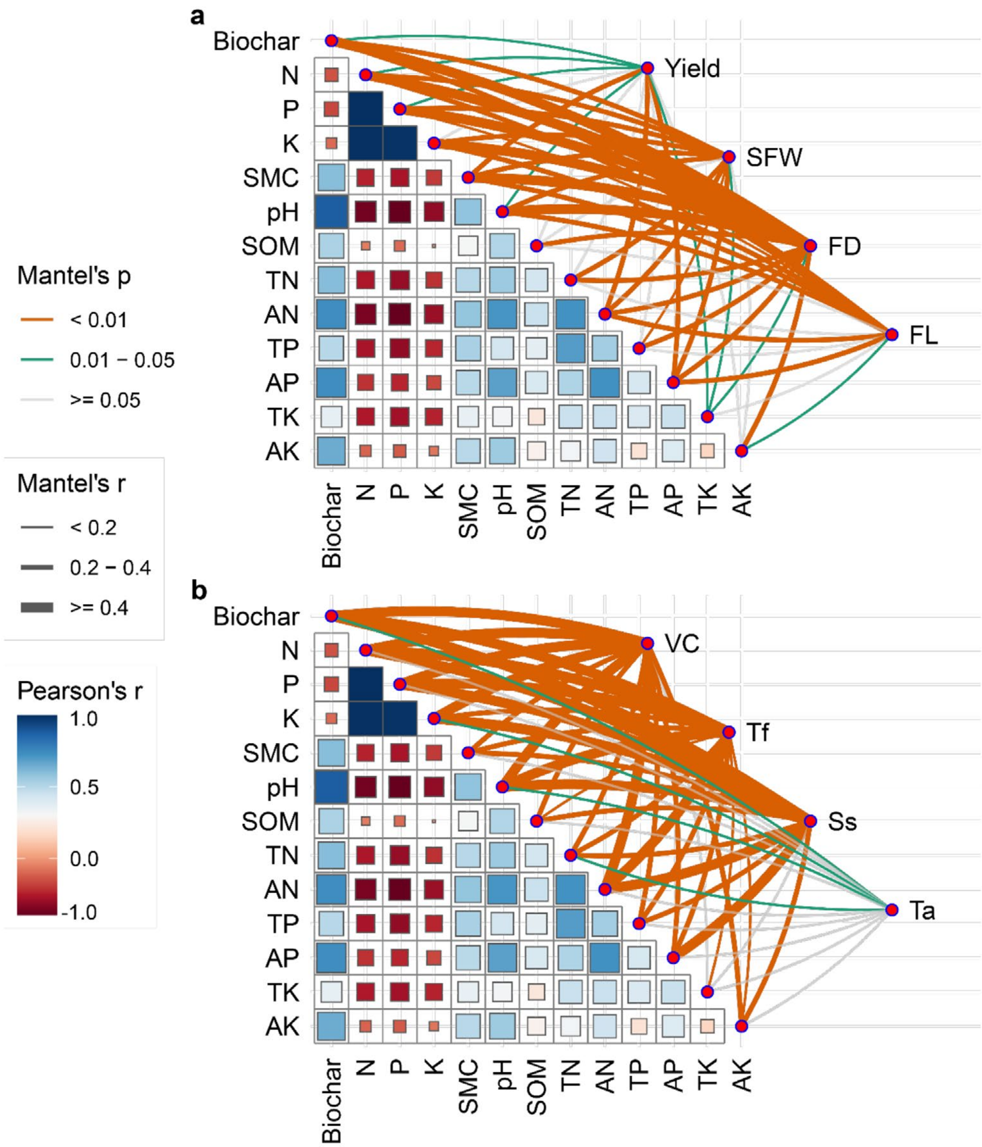

FIGURE 4 | Correlations between (a) fruit yield and (b) fruit quality parameters and biochar, nitrogen (N), phosphorus (P), and potassium (K), and soil properties in *R. roxburghii* cultivation system. Soil properties include soil moisture content, pH, organic matter, total nitrogen, available nitrogen, total phosphorus, available phosphorus, total potassium, and available potassium. Fruit yield indices include yield per plant, single fruit weight (SFW), transverse diameter (FD), and longitudinal diameter (FL). Fruit quality indices include Vitamin C content (VC), total flavonoids (Tf), soluble sugar content (Ss), and titratable acidity (Ta). Edge widths represent Mante's *r* values, with edge colors indicating statistical significance. The color scale represents Pearson's correlation coefficients for pairwise correlations between variables.

Biochar application showed significant effects on yield indices and quality indices, with differential responses observed across the application rates (Figure 6). Linear regression analyses revealed positive correlations between biochar application and yield indices and quality indices, including fruit yield ($R^2=0.26$, $p<0.01$), single fruit weight ($R^2=0.44$, $p<0.01$), fruit diameter ($R^2=0.66$, $p<0.01$), fruit length ($R^2=0.40$, $p<0.01$), Vitamin C content ($R^2=0.64$, $p<0.01$), total flavonoids ($R^2=0.65$, $p<0.01$), soluble sugar content ($R^2=0.77$, $p<0.01$), and titratable acidity ($R^2=0.12$, $p=0.02$). The integrated analysis of fertilizer effects, represented by the standardized NPK score, indicated a more pronounced influence on specific crop parameters compared to biochar application (Figure 6). These relationships were further modulated by soil moisture content, as evidenced by the varying responses across different moisture contents (Figure 6).

4 | Discussion

Investigation of biochar-based fertilizer effects on *R. roxburghii* cultivation systems has revealed complex interactions between soil amelioration processes and plant physiological responses. The observed improvements to soil physicochemical properties and subsequent impacts on fruit quality parameters warrant careful examination within the broader context of sustainable agriculture in Karst regions (Fornes et al. 2025; Yan et al. 2021).

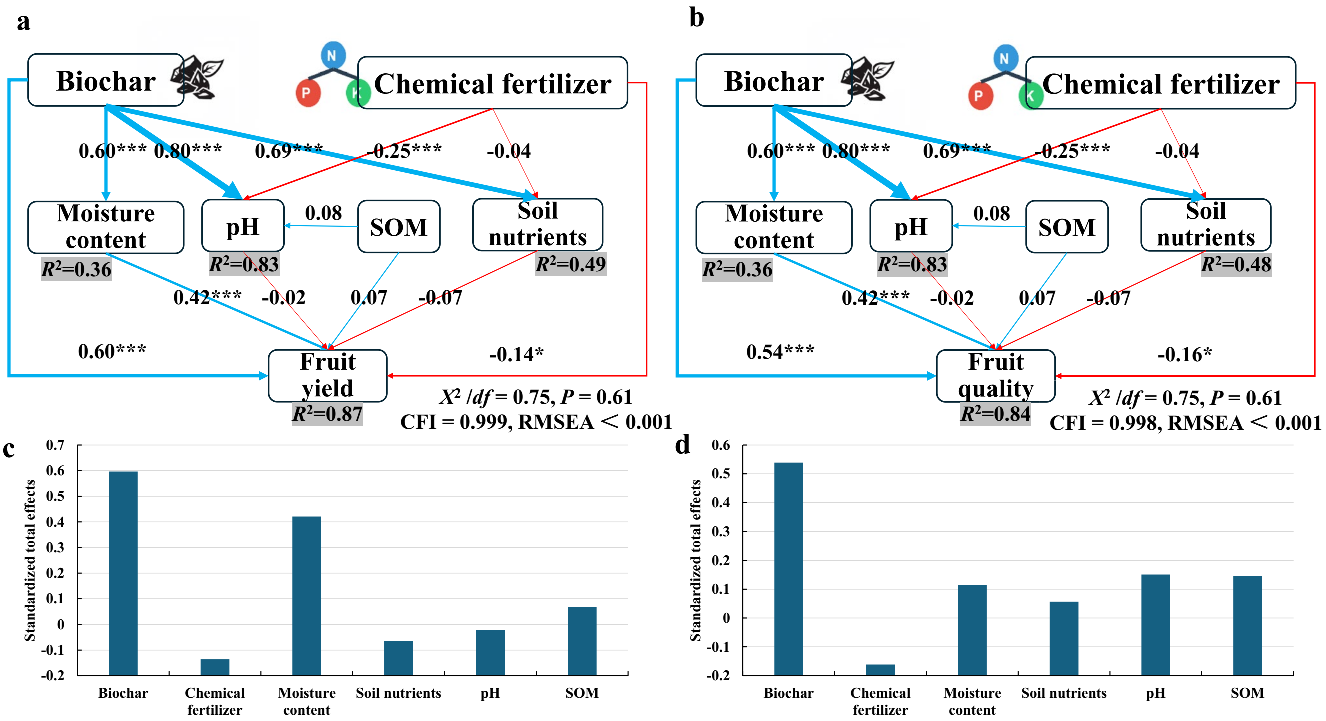

FIGURE 5 | Structural equation model depicting causal relationships between biochar-based fertilizer application, soil physicochemical properties, and (a) fruit yield and (b) fruit quality parameters in *R. roxburghii* cultivation system. Standardized total effects of (c) fruit yield and (d) fruit quality resulted from the SEM. Path coefficients (β) indicate strength and direction of relationships. Blue arrows represent positive effects, red arrows indicate negative effects. Arrow thickness proportional to coefficient magnitude. R^2 values indicate proportion of variance explained. ***, **, * represent significant effects at the $p<0.05$, $p<0.01$, $p<0.001$, respectively.

4.1 | Mechanisms of Soil Property Improvement

The substantial enhancement of soil moisture retention under RPB4 treatment (31.18% ± 1.24%, $p<0.05$) appears to derive from specific physicochemical properties of the biochar matrix. While previous investigations have documented biochar's capacity to modify soil hydrological properties (Chen et al. 2021; Zhao et al. 2022), the present study extends these findings by illustrating biochar feedstock-dependent variations in efficacy. The differential response to biochar feedstock source materials suggests that pore architecture and surface chemistry characteristics may exert a more significant influence on moisture dynamics than previously recognized (Wang and Wang 2019; Zhang et al. 2021).

Soil pH changes exhibited clear treatment-dependent patterns, with maximum elevation observed under RPB5 treatment (7.01 ± 0.08, $p<0.05$). This pH modulation exceeds previously reported values for similar amendments in Karst soils (N. Bolan, Sarmah, et al. 2023; Wang et al. 2022) and may reflect synergistic interactions between biochar surface properties and indigenous soil buffering mechanisms. The observed pH changes correlate strongly with enhanced nutrient availability ($r=0.82$, $p<0.001$), suggesting that pH change represents a primary mechanism through which biochar influences soil fertility parameters.

The marked increase in soil organic matter content under optimal treatments (42.44 ± 1.37 g kg^{-1}, $p<0.05$) warrants particular attention, as it deviates from theoretical predictions based on simple additive effects. This observation suggests that biochar amendment may stimulate indigenous organic matter accumulation processes, possibly through changes in microbial community dynamics or enhancement of plant root exudation patterns (Rombel et al. 2022; Yang et al. 2022). Such mechanisms require further investigation through detailed molecular and microbiological analyses.

4.2 | Nutrient Dynamics and Bioavailability Mechanisms

The differential patterns observed in nitrogen availability metrics reveal complex transformation processes that transcend simple retention mechanisms. Total nitrogen maximization under RPB3 treatment (1.35 ± 0.04 g kg^{-1}, $p<0.05$) contrasts with available nitrogen optimization under RPB4 conditions (69.41 ± 2.15 mg kg^{-1}, $p<0.05$), suggesting complex modifications to nitrogen cycling pathways. This dichotomy extends beyond previous mechanistic proposals (Li et al. 2020, 2023) and indicates potential alterations to microbial-mediated nitrogen transformation processes.

The enhancement of phosphorus availability under RPB4 treatment (46.75 ± 1.45 mg kg^{-1}, $p<0.05$) represents a significant advance in addressing the characteristic phosphorus limitations of Karst soils. Strong negative correlations between available phosphorus and extractable calcium ($r=-0.76$, $p<0.01$) suggest that biochar amendment modifies phosphorus–calcium interaction dynamics, potentially through alteration of soil

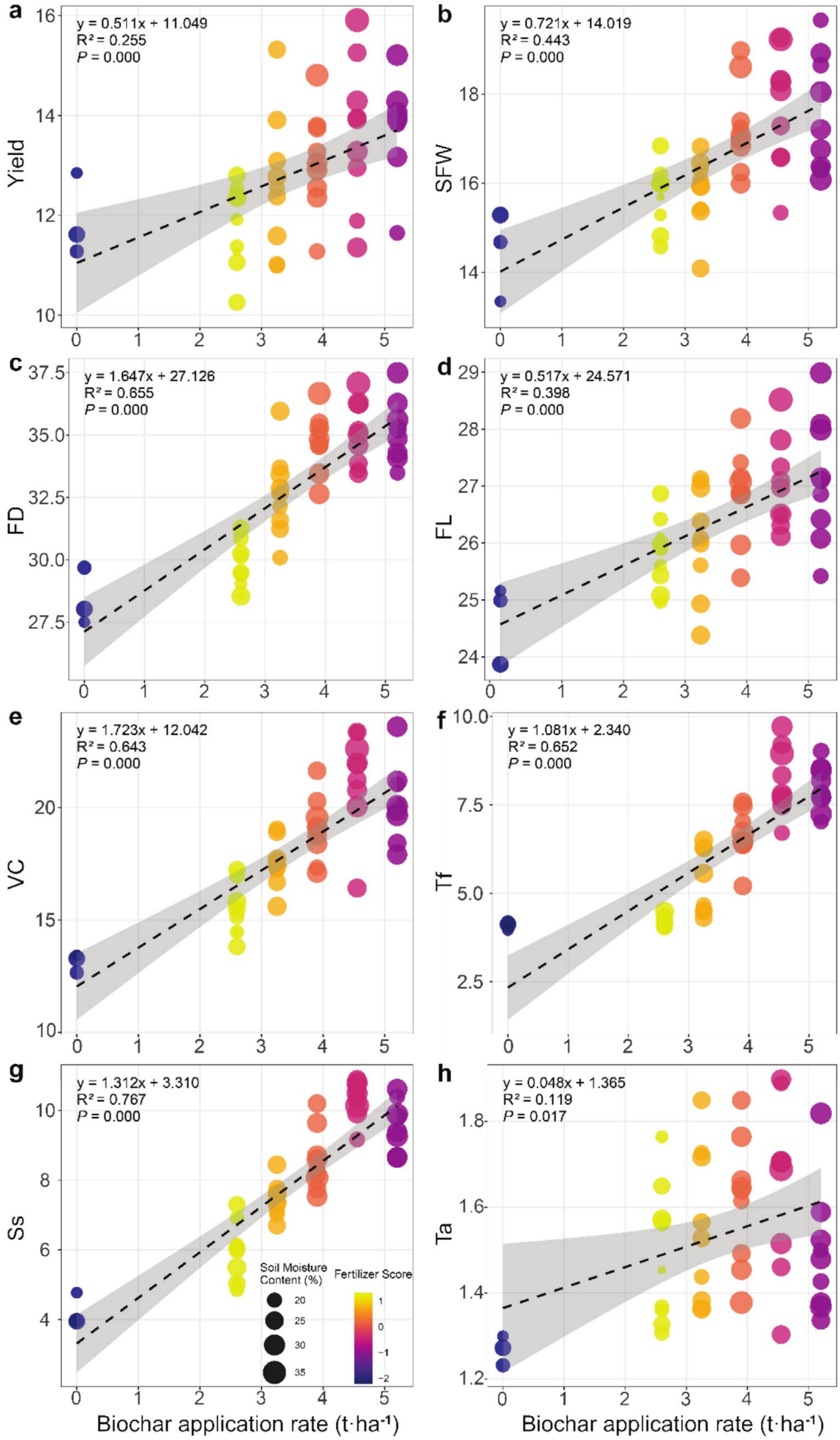

FIGURE 6 | Relationships between biochar application rate and various fruit yield and quality indices. Effects on yield-related parameters including (a) fruit yield (Yield), (b) single fruit weight (SFW), (c) fruit diameter (FD), and (d) fruit length (FL). Effects on fruit quality indices including (e) vitamin C content (VC), (f) total flavonoids (Tf), (g) soluble sugar (Ss), and (h) titratable acid (Ta). Point sizes represent soil moisture content (%), while color gradients indicate the combined fertilizer effect score (integrated nitrogen (N), phosphorus (P), and potassium (K) fertilizers application rates). The dashed lines represent linear regression fits, with corresponding equations, R^2 values, and p-values.

solution chemistry and surface complexation processes (Deng et al. 2024).

The observed strong correlations between improved soil properties and enhanced fruit quality under biochar amendment can be attributed to a cascade of biochar-mediated mechanisms that optimize the soil–plant–microbe continuum. Primarily, biochar's porous structure and high surface area enhance soil moisture retention (Zhang et al. 2021) and provide a protected habitat for beneficial microbial communities, thereby increasing microbial abundance and activity (Bolan, Hou, et al. 2023; Bolan, Sarmah, et al. 2023; Hu et al. 2024). This shift in microbial dynamics is crucial for nutrient cycling, as a more robust microbial population accelerates the mineralization of organic matter, releasing plant-available nutrients like nitrogen, phosphorus, and potassium (Xia et al. 2024). The subsequent improvement in nutrient uptake efficiency, particularly for potassium, which is vital for sugar translocation and enzyme activation, directly promotes the accumulation of primary metabolites like soluble sugars (Hossain et al. 2020). Furthermore, the stabilization of soil pH towards neutral optimizes the activity of rhizosphere microbes and root function, facilitating the absorption of micronutrients essential for the biosynthesis of secondary metabolites. For instance, improved uptake of elements like molybdenum and zinc can act as cofactors for key enzymes involved in the ascorbate–glutathione cycle, boosting Vitamin C synthesis (Khaliq et al. 2023). The enhanced carbon availability from biochar and stabilized soil organic matter also provides the foundational carbon skeletons and energy required for the phenylpropanoid pathway, leading to the significant increase in flavonoid content observed in our study.

4.3 | Integration of Plant Physiological Responses and Quality Parameters

The marked enhancement of fruit quality metrics under biochar treatments indicates modulation of plant physiological processes. Vitamin C accumulation reached a maximum under DMB4 treatment ($22.04 \pm 0.66\,\mathrm{mg\,g^{-1}}$, $p < 0.001$), while total flavonoid content peaked under RPB4 conditions ($9.00 \pm 0.27\,\mathrm{mg\,g^{-1}}$, $p < 0.001$). These improvements significantly exceed previously reported enhancements in similar fruit crops (Huang et al. 2023) and suggest changes in plant secondary metabolite biosynthesis pathways. The temporal correlation between soil pH stabilization and enhanced metabolite accumulation ($r = 0.79$, $p < 0.001$) indicates potential pH-mediated regulation of key biosynthetic enzymes (Yin et al. 2024).

Soluble sugar accumulation under RPB4 treatment ($10.52\% \pm 0.32\%$, $p < 0.001$) demonstrates coordinated enhancement of primary metabolic processes. The observed sugar-flavonoid correlation ($r = 0.85$, $p < 0.001$) suggests that biochar-induced modifications to soil conditions may simultaneously enhance photosynthetic efficiency and carbon allocation to secondary metabolite pathways (Hossain et al. 2020; Khaliq et al. 2023). This hypothesis is supported by the structural equation modeling results ($\beta = 0.15$, $p < 0.05$) linking soil organic matter content to fruit quality parameters.

4.4 | Mechanisms of Enhancing Soil Physicochemical Properties and Fruit Quality With Application of Biochar-Based Fertilizer

The enhancement of soil properties and fruit quality parameters through biochar application appears to operate through multiple interconnected mechanisms. Multivariate analysis revealed that available potassium and organic matter served as primary drivers of soil improvement, consistent with mechanistic studies of biochar-mediated nutrient dynamics (Xia et al. 2024). The strong loading of available potassium (0.14) likely reflects biochar's capacity to modify cation exchange processes through surface functional groups, as suggested in recent investigations of biochar surface chemistry (Pandian et al. 2024). This change in potassium availability may be particularly significant in karst soils, where calcium competition often limits nutrient accessibility (Yang et al. 2023).

The significant influence of organic matter content (0.13) on biochar-based fertilizer treatment efficacy suggests that biochar enhances soil quality through both direct and indirect mechanisms. Recent molecular analyses have reported that biochar-induced changes in soil organic matter composition can modify microbial community structure and enzyme activities, potentially explaining the observed enhancement in nutrient availability (Hu et al. 2024). These findings align with emerging models of biochar-microbe interactions in agricultural soils (Hu et al. 2024; Yan et al. 2021; Zhang et al. 2021).

Structural equation modeling revealed distinct causal pathways through which biochar influences soil–plant interactions. The strong direct effects on soil water content ($\beta = 0.60$, $p < 0.001$) likely derive from biochar's hierarchical pore structure and surface hydrophilicity, mechanisms elucidated through advanced microscopy studies (Qi et al. 2023). The significant pH change (0.80, $p < 0.001$) may reflect both direct alkalinity contribution and enhanced soil buffering capacity, as suggested by investigations of biochar aging in agricultural soils (Sun et al. 2023).

The observed antagonistic interaction between chemical fertilizers and soil pH (−0.25, $p < 0.001$) provides mechanistic insight into the importance of optimizing biochar-fertilizer ratios. This relationship likely reflects proton generation during nitrogen transformation processes, a mechanism recently detailed in studies of fertilizer-induced acidification (Bhattacharyya et al. 2024). Biochar's capacity to buffer these acidification effects may explain the superior performance of higher biochar ratios in our study, supporting theoretical models of biochar-fertilizer synergies (Chen et al. 2023).

The enhancement of fruit quality parameters appears to operate through complex soil–plant signaling pathways. Recent metabolomic analyses have indicated that biochar-induced changes in rhizosphere chemistry can influence plant secondary metabolism (Ferreira et al. 2024), potentially explaining the observed improvements in fruit nutritional content. The strong correlation between soil organic matter and fruit quality parameters suggests that biochar may enhance fruit development through changes in root-microbe interactions, a mechanism increasingly recognized in studies of biochar effects on fruit crops (Bhattacharyya et al. 2024).

4.5 | Implications for Sustainable Agricultural Systems

The superior performance of RPB4 treatment across multiple soil and plant response parameters suggests particular efficacy of locally-sourced biochar materials in Karst agricultural systems. The observed enhancement of soil physical properties (moisture retention: +61.37%, $p < 0.05$) coupled with improved nutrient availability (available nitrogen: +22.74%, $p < 0.05$) indicates potential for simultaneous amelioration of multiple plant growth-limiting factors in Karst soils. These improvements, combined with enhanced fruit quality parameters, suggest significant potential for biochar-based fertilizers in sustainable orchard management strategies.

However, several critical considerations emerge from the current investigation. The differential response patterns between soil parameters and fruit quality metrics indicate complex optimization requirements for practical implementation. The time-dependent nature of observed improvements suggests potential variation in treatment efficacy across growing seasons, necessitating long-term evaluation of stability and persistence. Additionally, the economic feasibility of scaled production requires careful assessment within specific agricultural contexts.

Beyond these agronomic benefits, our study demonstrates that the application of biochar-based fertilizers derived from local agricultural waste (e.g., *R. roxburghii* pomace, chili straw) offers significant economic and environmental advantages, particularly relevant to Karst regions. Economically, utilizing local pomace or straw as feedstock not only reduces waste disposal costs but also creates value from previously underutilized resources, potentially lowering long-term reliance and expenditure on chemical fertilizers. Environmentally, this waste valorization strategy supports a circular agricultural economy by enhancing soil organic carbon sequestration and mitigating the risks of nutrient leaching in these fragile Karst ecosystems, which are highly susceptible to environmental degradation. The superior performance of the RPB4 treatment, which utilized locally sourced pomace, underscores the potential of this approach to integrate productivity enhancement with ecological restoration, providing a holistic strategy for sustainable agriculture in fragile landscapes.

4.6 | Research Limitations and Future Directions

The current study, while demonstrating significant advances in understanding biochar-soil–plant interactions, reveals several critical knowledge gaps requiring attention. Temporal constraints of the single-season study limit assessment of long-term stability and cumulative effects. The precise molecular mechanisms underlying observed improvements in nutrient availability and metabolite accumulation remain to be fully elucidated. Furthermore, the potential role of soil microbiota in mediating observed responses warrants detailed investigation through modern molecular techniques. While this study demonstrates significant short-term benefits, the long-term persistence of these improvements requires further investigation. Future research should focus on multi-season trials to monitor the stability of soil carbon sequestration, nutrient retention capacity, and microbial community shifts induced by biochar. Understanding the duration of agronomic effects and potential risks of nutrient imbalance is crucial for validating the sustainable application of biochar-based fertilizers in Karst orchards. Future research priorities should include long-term field trials examining treatment stability and cumulative effects through detailed temporal monitoring of soil and plant parameters, or economic and environmental assessment of scaled implementation using life cycle analysis approaches.

5 | Conclusions

This study revealed the substantial benefits of biochar-based fertilizers in enhancing soil physicochemical properties, increasing yield, and improving the nutritional quality of *R. roxburghii* fruits in Karst regions. Specifically, the RPB4 treatment increased soil moisture by 61.4%, soil pH by 19.5%, and soil organic matter by 28.1%. These soil improvements directly contributed to a 20.6% increase in fruit yield and a 67.9% rise in vitamin C content. The study highlights the multifaceted role of biochar in promoting sustainable agriculture by enhancing soil fertility, water retention, and crop quality. Furthermore, the use of locally sourced agricultural by-products for biochar production adds value to agricultural residues and minimizes environmental impact. While these findings provide a strong foundation for adopting biochar-based fertilizers in Karst agriculture, future research should explore long-term effects, microbial interactions, and economic feasibility to ensure broader applicability and scalability. By addressing both soil and crop challenges, this approach offers a replicable model for sustainable agricultural practices in environmentally fragile regions.

Author Contributions

Yangzhou Xiang: data analysis, visualization, writing – original draft, funding acquisition. **Jun Luo:** data analysis, visualization, writing – original draft, funding acquisition. **Ying Liu:** data collection, funding acquisition. **Yang Luo:** writing – review and editing. **Nanthi Bolan:** writing – review and editing. **Narasinha J. Shurpali:** writing – review and editing. **Hem Raj Bhattarai:** writing – review and editing. **Kadambot H. M. Siddique:** writing – review and editing. **Jing Fan:** designed research, writing – review and editing, funding acquisition. **Yuan Li:** designed research, writing – review and editing, funding acquisition.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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