horticulturae

Essay

Enhancing Soil Fertility and Elevating Pecan Fruit Quality through Combined Chemical and Organic Fertilization Practices

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Citation: Tong, Y.; Wang, Z.; Gong, D.; Huang, C.; Ma, X.; Ma, X.; Yuan, F.; Fu, S.; Feng, C. Enhancing Soil Fertility and Elevating Pecan Fruit Quality through Combined Chemical and Organic Fertilization Practices. *Horticulturae* **2024**, *10*, 25. https://doi.org/10.3390/horticulturae10010025

Academic Editors: Francesco De Mastro, Gennaro Brunetti, Karam Farrag and Huadong Zang

Received: 9 November 2023
Revised: 19 December 2023
Accepted: 22 December 2023
Published: 26 December 2023

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

Abstract: This study focused on 6-year-old 'Pawnee' pecan trees to elucidate the differential responses of physicochemical properties of orchard soil and pecan fruit quality when combining chemical and organic fertilizers. The aim was to unveil the mechanisms that underlie the effects of different fertilization treatments on soil fertility, soil enzyme activities, and pecan fruit quality. Four treatments were established: sole chemical fertilizer (CF; N:P_2O_5:K_2O is 15:15:15), chemical fertilizer combined with cake fertilizer (CF+CC), chemical fertilizer combined with manure fertilizer (CF+M), and chemical fertilizer combined with cake and manure fertilizer (CF+CC+M). Measurements were taken to assess the soil nutrient content, soil enzyme activities, and fruit growth quality in some orchards under different fertilization treatments. The results revealed that the combined application could increase yield and enhance pecan quality. Among these, the CF+M+CC treatment demonstrated the most favorable outcomes, with the pecan kernel oil and unsaturated fatty acid contents reaching 72.33% and 97.54%, respectively. The combined fertilization treatments had no significant impacts on soil trace elements such as Mg, Cu, and Mn; however, it significantly increased the Available Phosphorus (AP), Total Nitrogen (TN), Soil Organic Matter (SOM) and S-ACP (soil acid phosphatase) activities. In summary, the combined application of chemical and organic fertilizers can significantly increase the soil nutrient content and enzyme activities in pecan orchards, to promote the enhancement of fruit quality and economic aspects.

Keywords: pecan; chemical fertilizer; organic fertilizers; soil fertility; quality of pecan fruits

1. Introduction

Fertilizers can quickly provide plants with the nutrients they require to support high crop yields and contribute to feeding an expanding global population. However, certain chemical fertilizers can bind to the soil and cause acidification [1], or are lost via leaching, runoff, and erosion, which reach waterbodies and contribute to eutrophication [2]. Phosphorus (P)-induced modification of microbial communities alters both microbial activities and carbon (C) cycling rates [3,4], which leads to a reduction in the SOM content and soil fertility [5]. This inhibits plant growth, reduces fruit yields, and reduces their quality [6,7]. Thus, it is necessary to develop prudent and sustainable management practices that can mitigate any deleterious environmental costs.

Organic fertilizers have several advantages over chemical fertilizers, as they are rich in active organic matter that can improve the soil structure, increase the sequestration of soil C, and promote the growth and reproduction of soil microorganisms. The metabolic processes of these microorganisms can facilitate the conversion and decomposition of mineral nutrients in the soil. Moreover, organic fertilizers themselves contain a significant quantity of organic matter and nutrients, which can help to restore or maintain soil structure and fertility levels, leading to sustainable development [8,9]. Further, they can mitigate issues such as low nutrient utilization rates that may result from the application of only chemical fertilizers [10].

Compared with the sole use of chemical fertilizers, the synergistic effects of organic fertilizers in conjunction with chemical fertilizers result in greater accumulation of TN and organic matter in the soil. Research involving the proportional substitution of chemical fertilizers with different types of organic fertilizers indicated that the mixed application of chemical and organic fertilizers plays a pivotal role in crop growth, soil fertility, and sustainability, as opposed to the application of chemical fertilizer by itself. Additionally, this approach safeguards the local environment, making it an environmentally compatible management strategy for achieving sustainable development [11,12].

In recent years, research on the combined application of chemical and organic fertilizers has shown that in contrast to using chemical or organic fertilizers alone, their mutual application enhances the efficacy of nutrient absorption and utilization. This combined application of fertilizers has a significant positive impact on the soil pH, enzyme activities, and nutrient levels [13–15], which enhance sustainable soil productivity and inevitably lead to increased crop yields [16]. Furthermore, in other studies, this application has shown to improve the protein content, unsaturated fatty acids, and oil content of walnuts, while enhancing fruit quality. Simultaneously, it has a significant impact on economic traits such as yields, fruit diameters, and other measurable parameters [17,18].

Organic fertilizers have the capacity to increase the soil microbial biomass and enhance soil biodiversity [19]. They can provide soil microbes with more readily available C and N sources, improve the ecological environment for soil microorganisms, and promote microbial activities [20,21]. As vital components of organic matter, soil microorganisms respond more quickly to fertilization compared to overall SOM [22,23]. Previous research has verified that replacing a higher proportion of chemical fertilizers with organic counterparts can significantly reduce soil acidification, facilitate nutrient decomposition, increase microbial C and N content in the soil, enhance soil fertility, and boost soil enzyme activities [9,24]. Soil enzymes play critical roles in the decomposition of organic matter and nutrient cycling [25,26]. When crops require higher levels of nutrients than the soil can provide, increased soil enzyme activities can assist in breaking down microbes to release nutrients that were previously fixed in the soil, making them available for crop uptake and utilization [27].

Pecan (*Carya illinoinensis*) is a tree of the genus *Carya* in the Juglandaceae, which is native to Northern Mexico and the Southern United States [28]. Pecans have a thin shell and are prized for their high oil content, averaging 72.0% in unroasted kernels [29–31]. They are rich in unsaturated fatty acids and antioxidants, which makes them highly valuable for the market [32]. Thus, various fertilization management strategies are employed to increase and optimize pecan yield. For instance, fertilization plays a crucial role in enhancing the supply of soil nutrients, ensuring walnut growth, and improving fruit quality [33]. Currently, the research on the application of pecan fertilizer is limited. Therefore, this experiment focused on the 'Pawnee' pecan and primarily investigated the effects of the mixed application of chemical and organic fertilizers on fruit growth, quality, as well as soil fertility and enzyme activities in pecan orchard soils. The main objectives of this research were twofold: 1. To identify suitable fertilizer types that effectively enhance pecan quality and soil fertility. 2. To analyze the interrelations between various ecological factors that affect pecan growth, with the aim of providing a basis for rational fertilization practices to optimize its cultivation.

2. Materials and Methods

2.1. Study Area

The experimental site is in Jiulong Town (115°33′44″ E, 32°57′25″ N), Yingzhou District, in Fuyang City, of Anhui Province, China. This area receives an average annual rainfall of

837.5 mm and temperature of 15.3 °C, with 2400 h of full sunlight per year, and a 210 day frost-free period. The main types of soil are sandy. The long-term fertilization experiment began in the spring of 2017 and has been applied for 5 years. chemical fertilizer with ratios of N:P_2O_5:K_2O is 15:15:15 (STANLEY Compound fertilizer); Cake fertilizer is rapeseed cake, the organic matter content in cake meal fertilizer was 60%, N: 114 g·kg^{-1}, P: 95 g·kg^{-1}, K: 80 g·kg^{-1}; Manure fertilizer is cow and goat manure compost, the organic matter and amino acid content in the manure were 40% and 10%, N: 71 g·kg^{-1}, P: 66 g·kg^{-1}, K: 53 g·kg^{-1}.The fundamental physicochemical properties of the soil as 2017: pH = 7.63, SOM 7.52 g·kg^{-1}, TN 50.24 mg·kg^{-1}, AP 1.12 mg·kg^{-1}, and K 6.78 mg·kg^{-1}.

2.2. Experimental

Design. 6-year-old 'Pawnee' Pecan trees were selected for the experiment. The trees were spaced at intervals of 5 m by 6 m, and their growth was uniform. There were four treatments with four replicates each: (1) Chemical fertilizer (CF) (100% chemical fertilizer); (2) Chemical fertilizer + cake fertilizer (CF+CC) (50% chemical fertilizer and 50% cake fertilizer); (3) Chemical fertilizer + manure fertilizer (CF+M) (50% chemical fertilizer and 50% manure fertilizer); (4) Chemical fertilizer + manure fertilizer + cake fertilizer (CF+M+CC) (50% chemical fertilizer, 25% *cake* fertilizer, and 25% manure fertilizer). For the CF+CC, CF+M, and CF+M+CC treatments the amounts of chemical fertilizer were halved, and the reduced fertilizer amount was replaced with organic fertilizer in terms of N, P, and K. At the local custom chemical fertilizer application amount. Each treatment was repeated three times and covered an area of 667 m^2 (Table 1). This fertilization experiment began in 2017 and was conducted annually annually after the walnut harvest. Prior to application, the different ratios of fertilizers were thoroughly mixed and placed in trench-like grooves, which were then uniformly mixed with the topsoil and covered. All other fertilizer, water, and management conditions remained consistent.

Table 1. Experimental design.

Treatment	Chemical Fertilizer (kg·hm^{-2})			Cake Fertilizer (kg·hm^{-2})	Manure Fertilizer (kg·hm^{-2})
	N	P_2O_5	K_2O		
CF	150	150	150	0	0
CF+CC	75	75	75	720	0
CF+M	75	75	75	0	1350
CF+M+CC	75	75	75	360	675

Note: 100% chemical fertilizer (CF); 50% chemical fertilizer and 50% cake fertilizer (CF+CC); 50% chemical fertilizer and 50% manure fertilizer (CF+M); 50% chemical fertilizer, 25% Manure fertilizer, and 25% cake fertilizer (CF+M+CC).

2.3. Laboratory Analysis

Individual trees with consistent growth, free of pests and diseases, were selected on 10 October 2022. From each tree, five fruits were randomly selected from three different levels within the canopy (upper, middle, and lower), as well as from the outer perimeter for a total of 30 sample fruits. Following the removal of the green skin when the fruits were ripe, they were naturally air-dried and their fruit and kernels were weighed. Additional measurements were made to quantify the individual fruit height, fruit diameter, and shell thickness. The oil was measured using the Soxhlet extraction technique [34], fatty acid content using the GC-MS external standard method [35], Sample 0.2 g of oil saponification and methyl ester treatment, GC-MS analysis was performed by Agilent 7890A and 5975C (Agilent Technology, Santa Clara, CA, USA). Chromatographic analysis conditions: DB-225MS column (30 m × 0.25 mm, 0.25 μm; Agilent Technology, USA). The carrier gas was helium, and the purge flow rate of the spacer was 3.0 mL·min^{-1}. Heating procedure: initial temperature 50 °C, 1 min; The temperature was first raised to 200 °C at the rate of 5 °C·min^{-1}, and then to 230 °C at the rate of 2 °C·min^{-1} for 10 min. Forward sample temperature 250 °C, transmission line temperature 250 °C, ion source temperature 230 °C, four-stage rod temperature 150 °C, ionization voltage −70 eV. Four replicate plots were established for each treatment, and soil samples were extracted from multiple sampling points within each plot, the soil sampling was carried out up to a depth of 40 cm, excluding the superficial vegetative layer. The mixed soil samples were subjected to physicochemical analysis, Soil pH was determined with a glass electrode (soil:water = 1:2.5) pH instrument(Mettler Toledo, Shanghai, China), Soil EC was determined with a glass electrode (soil:water = 1:5) EC meter (Mettler Toledo, Shanghai, China),with soil AP, TP, NH_4^+-N, NO_3^--N, TN, using an automated continuous chemical analyzer (De Chem-Tech, Clever Chem Anna, Germany) extractants by vitriol [36]. To measure available K, Mg, Fe, Zn, Mn, and copper (Cu), soil samples were extracted by Ammonium bicarbonate diethylenetriaminepentaacetic acid (DTPA) (AB-DTPA) [37]. The soil enzyme activity was assessed following the methods of Sun [38], Kandeler [39], and Taylor [40], with enzyme activities expressed in international units per gram of soil consumed ($U \cdot g^{-1}$).

2.4. Data Analysis

All data analysis was performed in R 4.1.3. to test whether they met the normal distribution, and then complete statistical analysis. The resulting data were presented as mean values and standard errors. Data were statistically analyzed via one-way ANOVA with repeated measures and the post hoc method (Duncan's method), for multiple comparisons at a 5% significance level. A Pearson's correlation matrix was generated between the fruit quality and soil parameters. Redundancy analysis (RDA) in Canoco5.0 was applied to explore the correlations between environmental factors, soil enzyme activities, and soil nutrient elements.

3. Results

3.1. Subsection Effects of Different Fertilization Treatments on Pecan Yield

With the use of fertilizers combined with manure, cake fertilizer and the other three kinds of fertilizer combinations, the yield of thin-shell pecan showed an increasing trend (Table 2). The combined application of the three fertilizers increased yields to 598.34 $kg \cdot hm^{-2}$, 583.73 $kg \cdot hm^{-2}$ and 618.87 $kg \cdot hm^{-2}$, respectively, in 2022, as compared with 2018. Compared with 2018 and 2020, the output of thin-shell pecan in 2022 increased significantly, and the output of each treatment in 2022 increased successively: CF+M+CC > CF+M > CF+CC > CF. By 2022, CF+M, CF+CC and CF+M+CC treatments had the highest yield increases of 13.02% for CF+M+CC, followed by 10.34% for CF+M and 8.03% for CF+CC.

Table 2. Effects of different fertilization treatments on pecan yield.

Treatment	2018 ($kg \cdot hm^{-2}$)	2020 ($kg \cdot hm^{-2}$)	2022 ($kg \cdot hm^{-2}$)	2022 Comparison with CF	
				Production Increase ($kg \cdot hm^{-2}$)	Yield Increase Rate (%)
CF	756.51 ± 4.82 a	839.96 ± 4.78 a	1083.36 ± 10.42 d	-	-
CF+M	597.14 ± 3.99 bc	768.67 ± 3.19 c	1195.48 ± 4.63 b	112	10.34
CF+CC	587.07 ± 2.58 c	782.14 ± 5.58 b	1170.8 ± 4.39 c	87	8.03
CF+M+CC	606.1 ± 6.03 b	792.53 ± 2.93 b	1224.97 ± 5.91 a	141	13.02

Different letters indicate significant differences between the treatments.

3.2. Effects of Different Fertilization Treatments on Fruit Traits of Pecan Nuts

Among the four different fertilization treatments applied to pecan, economic parameters such as nut mass, kernel weight, nut vertical and horizontal diameters exhibited significant differences between the sole application of chemical fertilizers and mixed application of inorganic and chemical fertilizers ($p < 0.05$). However, the kernel yield and shell thickness did not exhibit significant differences (Figure 1). In terms of the kernel weight (Figure 1B) and nut mass (Figure 1C), the CF+CC+M treatment yielded the highest values (7.18 g and 12.75 g, respectively), with increases of 1.65 g and 3.38 g, respectively, as compared with the CF treatment. Furthermore, the CF+CC+M treatment demonstrated the highest kernel yield, exceeding that of the CF treatment by 7.64% (Figure 1A). This difference may have been related to the thickness of the pecan shells. Regarding the nut vertical and horizontal diameters, the application of chemical fertilizers on their own resulted in values lower than those observed under treatments with additional organic fertilizers.

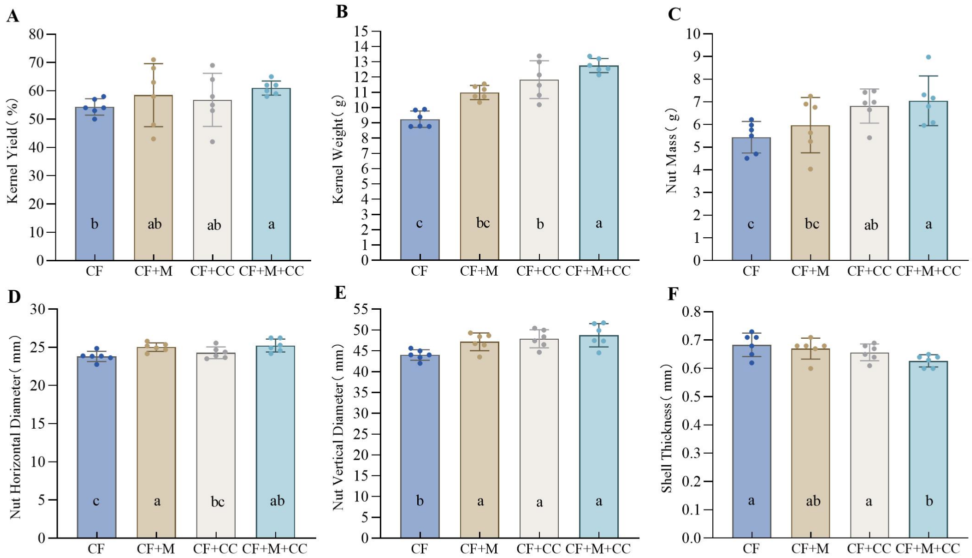

Figure 1. (**A**–**F**) Effects of different fertilization treatments on economic characteristics of pecan. Dots around the top of the bars represent the specific values of the five repetitions in the drawn bar chart. All data are the standard error means of five replicates±. The error bar shows the standard error. Different letters indicate significant differences between the treatments.

3.3. Effects of Different Fertilization Treatments on Nucleolar Nutritional Quality

Different fertilization treatments had varying degrees of influence on the oil content and unsaturated fatty acid content of pecans (Figure 2). Both were highest under the CF+CC+M treatment, which showed increases of 2.50% and 7.28%, respectively, in contrast to the CF treatment. When considering the contents of octadecenoic acid (C18:1), octadecadienoic acid (C18:2), octadecatrienoic acid (C18:3), and gondoic acid (C20:1), it was observed that the monounsaturated fatty octadecenoic acid decreased (Figure 2D), while the contents of polyunsaturated fatty octadecadienoic acid (Figure 2E) and octadecatrienoic acid (Figure 2F) increased. The fertilization treatments were beneficial for increasing the unsaturated fatty acid content.

3.4. Effects of Different Fertilization Treatments on Soil pH, EC, and SOM

Under different fertilization conditions, the combined application of inorganic and chemical fertilizers significantly impacted the pH, EC, and SOM ($p < 0.05$) (Table 3). In contrast to the sole application of chemical fertilizers (CFs), treatments that incorporated organic fertilizers (e.g., CF+CC, CF+M, and CF+M+CC) demonstrated notable increases in pH of 1.42, 1.3, and 1.41, decreases in EC of 15.56%, 18.52%, and 14.07%, and improvements in SOM of 64.3%, 66.5%, and 122%, respectively.

Table 3. Effects of different fertilization treatments on soil pH, EC, and SOM.

Treatment	pH	EC (ds·m^{-1})	SOM (g·kg^{-1})
CF	6.93 ± 0.08 b	1.35 ± 0.02 a	12.67 ± 1.42 b
CF+M	8.23 ± 0.06 a	1.10 ± 0.03 b	21.09 ± 3.68 a
CF+CC	8.35 ± 0.06 a	1.14 ± 0.03 b	21.24 ± 1.25 a
CF+M+CC	8.34 ± 0.10 a	1.16 ± 0.03 b	28.33 ± 2.52 a

Different letters indicate significant differences between the treatments.

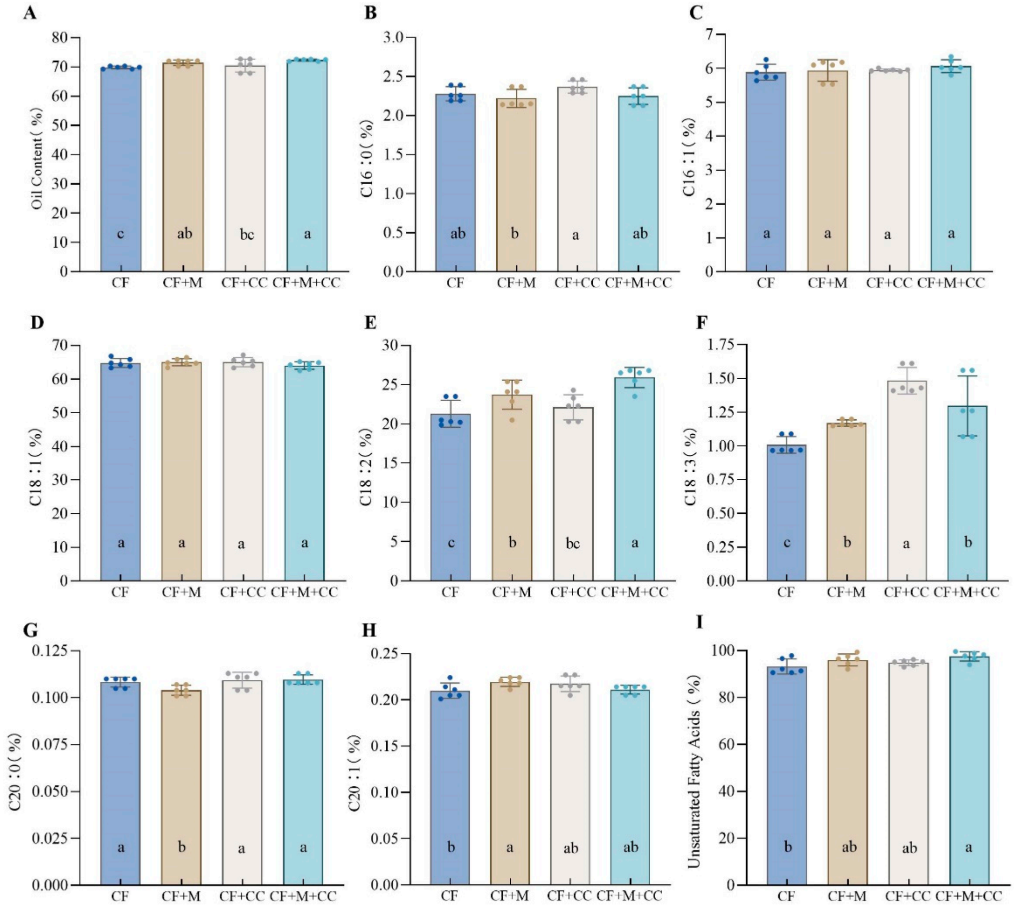

Figure 2. Effects of different fertilization treatments on nucleolar nutritional quality. (**A**) Oil content; (**B**) C16:0—hexadecanoic acid; (**C**) C16:1—palmitoleic acid; (**D**) C18:1—octadecenoic acid; (**E**) C18:2—octadecadienoic acid; (**F**) C18:3—octadecatrienoic acid; (**G**) C20:0—eicosanoic acid; (**H**) C20:1—gondoic acid; (**I**) unsaturated fatty acids. Dots around the top of the bars represent the specific values of the five repetitions in the drawn bar chart. All data are the standard error means of five replicates±. The error bar shows the standard error. Different letters indicate significant differences between the treatments.

3.5. Effects of Different Fertilization Treatments on Soil Nutrients

Under different fertilization conditions, the combined application of inorganic and chemical fertilizers significantly impacted the AP, NH_4^+-N, NO_3^--N, TN, and K levels ($p < 0.05$), while the TP content showed no significant differences (Figure 3). The CF treatment exhibited the lowest AP content (Figure 3C), at only 13.1% of CF+M+CC. Furthermore, NH_4^+-N (Figure 3A), NO_3^--N (Figure 3B), TN (Figure 3E), TP (Figure 3D), and K (Figure 3F) exhibited the highest levels under the CF+M+CC treatment, with increases of 75.5%, 465.1%, 15.5%, 7.8%, and 33.5%, respectively, as compared to the CF.

Treatments that involved the sole application of CF and combined application of chemical and organic fertilizers revealed significant differences in the soil Ca and Zn contents ($p < 0.05$), while the Mg and Cu contents showed no noticeable distinctions (Figure 4). The soil Zn content (Figure 4A) and Ca content (Figure 4D) reached their highest levels under the CF+M+CC treatment (4.21 mg·kg^{-1} and 1.54 mg·kg^{-1}, respectively). The soil Mg (Figure 4B) and Fe (Figure 4F) contents were highest under the CF+CC treatment, representing increases of 18% and 16% as compared to the CF. The soil Cu (Figure 4C) and Mn (Figure 4E) contents showed negligible differences between treatments; however, the CF+M showed the highest levels with increases of 7% and 26.8%, respectively, as compared to CF.

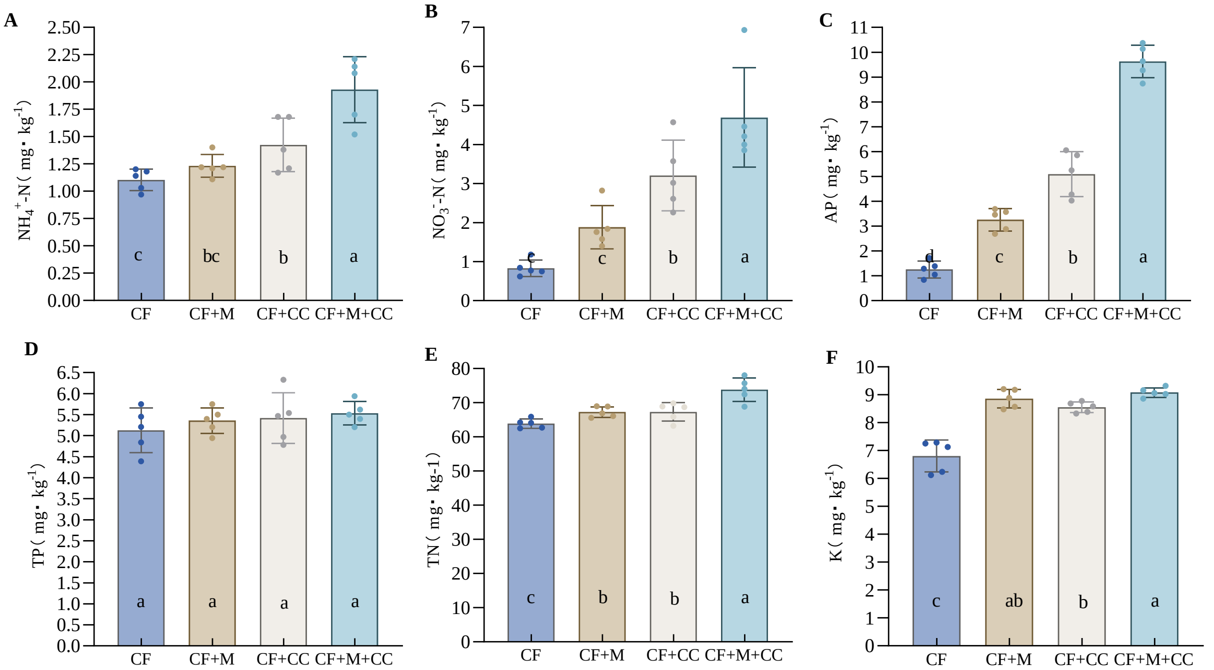

Figure 3. Effects of different fertilization treatments on soil nutrients. (**A**) NH_4^+-N content; (**B**) NO_3^--N content; (**C**) available P content; (**D**) total P content; (**E**) total N content; (**F**) total K content. Dots around the top of the bars represent the specific values of the five repetitions in the drawn bar chart. All data are the standard error means of five replicates±. The error bar shows the standard error. Different letters indicate significant differences between the treatments.

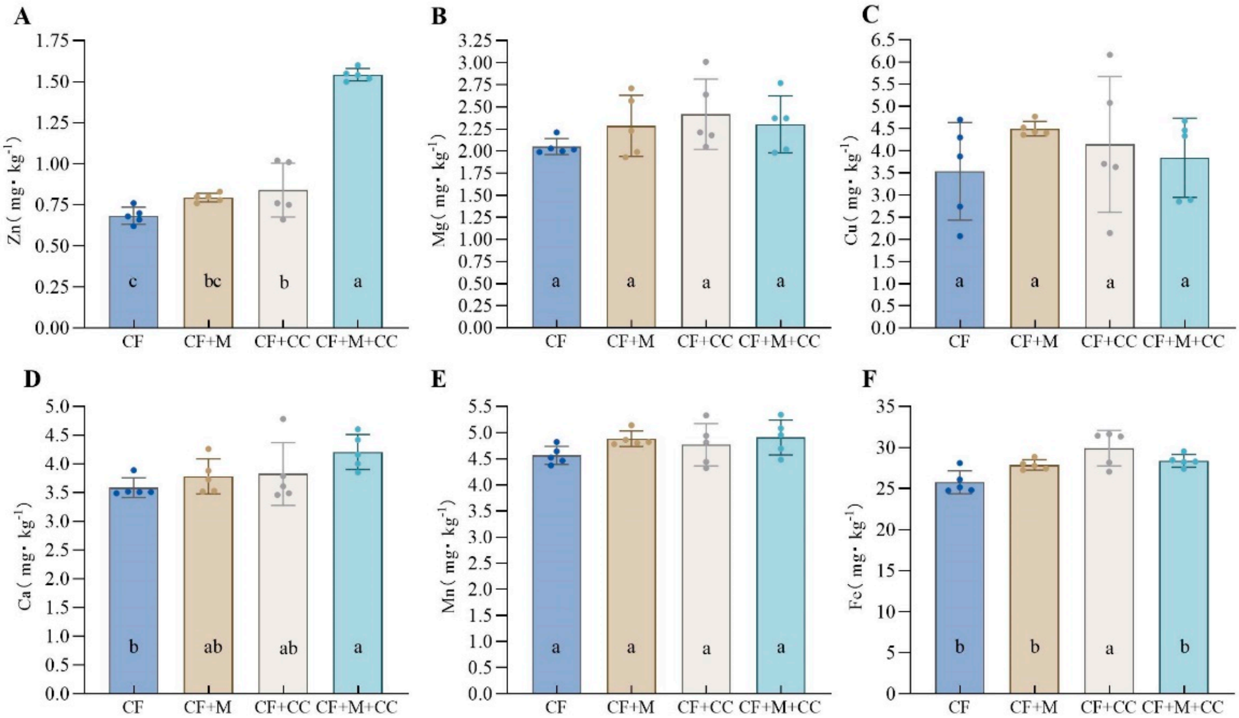

Figure 4. Effects of different fertilization treatments on soil nutrients. (**A**) Total Zn content; (**B**) total Mg content; (**C**) total Cu content; (**D**) total Ca content; (**E**) total Mn content; (**F**) total Fe content. Dots around the top of the bars represent the specific values of the five repetitions in the drawn bar chart. All data are the standard error means of five replicates±. The error bar shows the standard error. Different letters indicate significant differences between the treatments.

3.6. Effects of Different Fertilization Treatments on Soil Enzyme Activity

The various fertilization treatments exhibited varying degrees of influence on soil enzyme activities in the 0–20 cm soil layer (Figure 5). Significant differences ($p < 0.05$) were observed in soil urease (S-UE), soil peroxidase (S-POD), acid phosphatase (S-ACP), and saccharase (S-SC) between the treatments that involved inorganic fertilization by itself, and those that combined inorganic and organic fertilizers. Notably, the CF treatment exhibited the lowest activity levels in S-POD (Figure 5A), S-UE (Figure 5B), S-SC (Figure 5C), and S-ACP (Figure 5D), with differences that ranged from 28.9% to 153.0%, compared to the highest levels observed under the CF+M, CF+M+CC, CF+CC, and CF+M treatments.

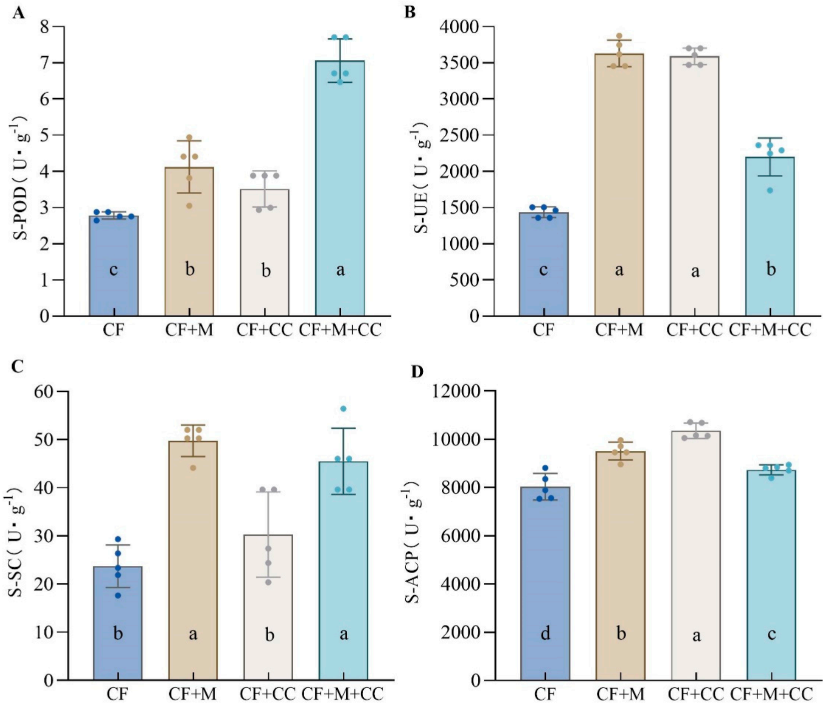

Figure 5. Effects of different fertilization treatments on soil enzyme activities. (**A**) S-POD: soil peroxidase; (**B**) S-UE: soil urease; (**C**) S-SC: saccharase; (**D**) S-ACP: acid phosphatase. Dots around the top of the bars represent the specific values of the five repetitions in the drawn bar chart. All data are the standard error means of five replicates±. The error bar shows the standard error. Different letters indicate significant differences between the treatments.

3.7. Correlation Analysis of Soil Nutrient and Enzyme Activities in Pecan

The yield exhibited significantly negative correlations ($p < 0.01$) with AP, NO_3^--N, Fe, S-UE, S-ACP, and showed significantly positive correlations ($p < 0.05$) withNH_4^+-N, K, Mg (Figure 6). The kernel weight exhibited significantly positive correlations with pH, SOM, AP, NH_4^+-N, NO_3^--N, TN, K, Ca, Fe, Zn, S-POD, S-UE and Mn, and negative correlations with EC. The kernel yields showed a significantly positive correlation with TN and no significant correlations with other nutrients and enzyme activities. The nut mass exhibited a significantly positive correlation with AP, as well as NH_4^+-N, NO_3^--N, Fe, and Zn. The nut vertical diameter exhibited significantly positive correlations with pH, AP, NO_3^--N, and S-POD, as well as with SOM, NH_4^+-N, TN, K, Zn, S-UE, and S-SC. The nut horizontal diameter exhibited significantly positive correlations with TN, K, Zn, S-POD, and S-SC, and negative correlations with EC. Furthermore, the shell thickness revealed significantly negative correlations with AP, NH_4^+-N, NO_3^--N, TN, TP, K, Ca, Mg, Fe, Mn, Zn, and S-POD, and negative correlations with pH. The oil content exhibited significantly positive correlations with AP, NO_3^--N, TN, K, Zn, and S-POD, as well as with SOM and NH_4^+-N, and showed negative correlations with EC. Unsaturated fatty acids showed a significantly positive correlation with S-POD, as well as with Zn and S-SC.

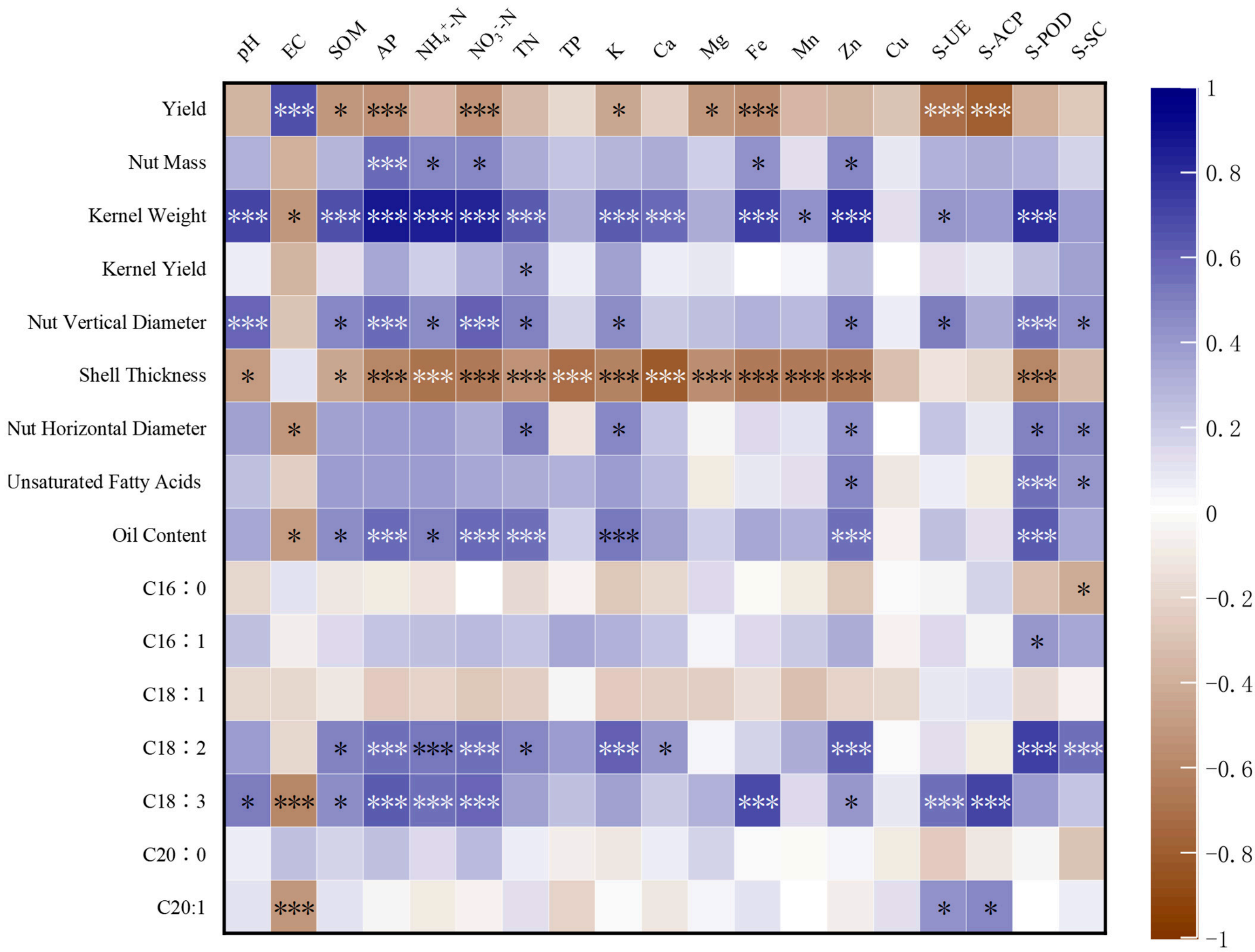

Figure 6. Analysis of fruit quality, soil nutrients, and enzyme activities of pecan under different fertilization treatments. ($p < 0.05$ *, $p < 0.01$ **, $p < 0.001$ ***).

C16:0 (hexadecanoic acid) and C16:1 (palmitoleic acid) revealed significantly positive correlations with S-SC and S-POD, respectively, and no significant correlations with other nutrients and enzyme activities. C18:2 exhibited significantly positive correlations with AP, NH_4^+-N, NO_3^--N, K, Zn, S-POD, and S-SC, as well as with SOC, TN, and Ca. C18:3 exhibited significantly positive correlations with AP, NH_4^+-N, NO_3^--N, Fe, S-UE, and S-ACP, as well as with pH, SOM and Zn, and showed significantly negative correlations with EC. C20:1 showed significantly positive correlations with S-UE and S-ACP, and significantly negative correlations with EC.

3.8. RDA Analysis of Soil and Quality of Pecan

Based on RDA analysis, we discerned the levels of influence of the fruit economic traits, soil nutrient factors, and soil enzyme activities on the quality of pecan fruits (Figure 7). For fruit quality and economic traits, the explanatory powers for the first and second axes were 34.77% and 3.49%, respectively, with a cumulative explanatory power of 38.26% (Figure 7A). For fruit quality and soil nutrients, the explanatory powers for the first and second axes were 54.01% and 7.15%, respectively, with a cumulative explanatory power of 61.16% (Figure 7B). For fruit quality and soil enzyme activities, the explanatory powers for the first and second axes were 19.34% and 9.02%, respectively, with a cumulative explanatory power of 28.36% (Figure 7C). Notably, the Zn, S-POD and nut vertical diameter, exhibited significant correlations with the pecan fruit quality ($p < 0.01$) (Table 4), while S-UE, NO_3^--N and the nut mass exhibited relatively weaker correlations with the pecan fruit quality.

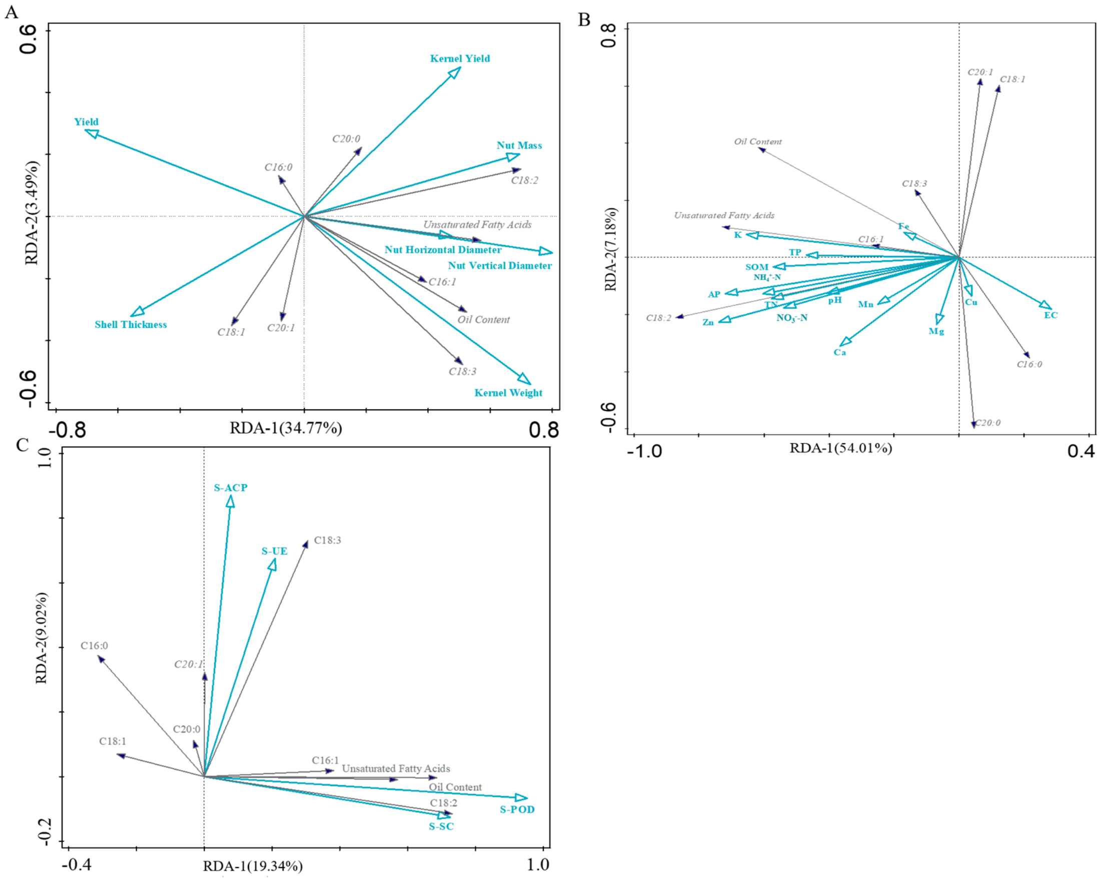

Figure 7. RDA plots showing the relationships between environmental factors and fruit traits (**A**), soil nutrients (**B**) and soil enzyme activities (**C**). Gray lines represent environmental variables, while blue lines represent fruit traits, soil nutrients, and soil enzyme activities.

Table 4. RDA data analysis table.

Name	Explains %	Contribution %	Pseudo-F	*p*
Zn	30.3	46.9	9.6	0.002
S-POD	18.1	52.5	4.9	0.002
Nut Vertical Diameter	22.3	55.8	6.3	0.006
Nut Mass	8.9	21.9	2.7	0.064
S-UE	7.8	22.5	2.2	0.07
NO_3^--N	7.3	11.2	2.5	0.088

4. Discussion

The application of organic fertilizers has direct impacts on both the accumulation and supply of soil nutrients, which is a critical step toward the reduction in our reliance on chemical fertilizers, and contributes to enhancing fruit quality and yield [16,41]. In this study, compared to CF, the CF+CC, CF+M, and CF+M+CC treatments significantly increased walnut yield, with the following yield ranking: CF+M+CC > CF+M > CF+CC. The introduction of organic fertilizers increases the activities of soil microorganisms, thereby accelerating the decomposition of organic compounds and enhancing the biological utilization of certain plant growth regulators, such as auxins, gibberellins, and essential nutrients [42,43]. Organic fertilizers are more effective than chemical fertilizers in increasing SOM content. As the SOM content increases, nitrogen fixation, sulfurization, and oxidation processes accelerate, which leads to the breakdown and release of certain less soluble nutrients [44–46]. The enriched organic matter improved soil structure and increased soil permeability. Under the joint action of the above aspects, the mineral nutrient content of the soil is increased, root growth and development is promoted, and the environment promotes the growth of pecan, thereby increasing yield [26]. The experimental results also showed that with the continuous use of organic fertilizer, the walnut yield of each fertilizer treatment would increase year by year. Studies have shown that soils with high nutrient content significantly improve leaf characteristics, photosynthetic rates, and stomatal conductance, thus leading to increased carbon accumulation, stabilized dry matter, and ultimately higher yields [47]. Correlation analysis in this study also indicates a highly significant relationship between soil N, P, and pecan yield. Mg and Fe play a crucial role in the quality of fruit tree yield. Balancing the supply and demand of nutrients in the soil for fruit trees throughout their entire growth period is essential to achieve high yields and quality.

The higher the content of unsaturated fatty acids and essential amino acids that cannot be synthesized by the human body, the better the nutritional quality of the nucleolar [48]. In this study, a comparison between mixed fertilization (CF+M+CC, CF+CC, and CF+M) treatments with exclusive chemical fertilizer (CF) treatments revealed significant improvements in the fruit oil and unsaturated fatty acid contents (Figure 2). While the content of the monounsaturated fatty acid C18:1 (octadecenoic acid) decreased in the kernel, there were increases in the contents of polyunsaturated fatty acids such as C18:2 (octadecadienoic acid) and C18:3 (octadecatrienoic acid). These results aligned with previous research findings [18,49]. In summary, the mixed application of organic and chemical fertilizers can provide balanced nutrition for pecan at different growth stages, thereby increasing pecan yield and improving kernel quality.

The most relevant chemical properties of soils are pH, electrical conductivity, fertility level, cation exchange capacity, and organic matter content. SOM is the most crucial foundational substance for soil fertility and a primary source of plant nutrition. Organic fertilizers contains abundant organic matter, which can promote the mineralization process of organic nutrients, improve soil pH, enhance soil fertility, and ameliorate soil quality [41,50]. In this study, it was observed that treatments involving the mixed application of chemical and organic fertilizers (CF+M+CC, CF+CC, and CF+M) significantly increased the SOM content and improved soil pH, in contrast to exclusive chemical fertilizer (CF) treatments. Furthermore, the mixed fertilizer treatments significantly elevated the levels of nutrients and micronutrients of the soil (Figures 3 and 4). Generally, the P content was significantly higher in neutral and alkaline than in highly acidic, acidic and slightly acidic soils. This is most likely because at higher pH, release of P from Al and Fe phosphates occurs. However, in highly alkaline soils, phosphate ions can easily form calcium phosphate precipitation with calcium ions, thus reducing the availability of phosphorus [51]. Plants can thrive within a broad range of soil pH values. However, the effectiveness of trace nutrients is closely associated with soil pH, and at higher pH levels, the availability of most trace nutrients to plant roots tends to be lower [52].

The combination of various organic fertilizers in the soil leads to nutritional advantages and potential. Studies have shown that mixed application of organic fertilizer increased the nutrient content of geranium (*Pelargonium* spp.). Soils where organic fertilizers were used tended to exhibit higher levels of N, P, K, Ca, and Mg [53,54]. The high SOM content of organic fertilizers may serve as chelating agents for certain elements, while enhancing the solubility and availability of nutrients in the soil [55,56]. Our findings were consistent in this respect, as they revealed higher levels of nutrient release through mixed organic fertilizer treatments for SOM and soil nutrients.

There is no doubt that the presence of microorganisms and their activity are vital for the normal and sustainable state of the soil. The introduction of organic fertilizers also improves the soil structure and quality, while enhancing microbial abundance and activities [57,58]. Soil enzyme activities are considered an indicator of the activities of soil microbes. Soil enzyme activity levels can reflect the attributes of soil microbes [59,60]. Our research revealed significant differences in the S-UE, S-SC, S-POD, and S-ACP activities between the application of only chemical fertilizers and mixed organic and chemical fertilizers. This suggested that the combination of chemical and organic fertilizers enhanced soil enzyme activities, which may be attributed to the significant improvement in soil physicochemical properties by organic fertilizers [11]. Long-term soil experiments at four locations in China revealed that the application of organic fertilizers enhanced most soil enzyme activities. They were observed to improve the networks between ion composition and soil enzyme activities in the soil in contrast to chemical fertilizers, which improved its dynamics and stability [61]. Studies by Ning et al. found that the combined application of chemical and organic fertilizers significantly increased SOM, S-POD, and S-UE activities [62]. Furthermore, the carbon content of organic fertilizers can serve as a significant carbon source for soil microorganisms [63]. S-UE, S-SC, S-POD, and S-ACP activities are closely related to soil C, N, and P cycling [64–67], which suggested that organic fertilizers substantially enhanced the activities of enzymes related to soil C, N, and P cycling [68]. In addition, organic fertilizers introduce beneficial microorganisms directly into the soil, and a variety of soil microorganisms can dissolve nutrients such as P, Fe, and Zn, thereby further improving soil enzyme activity.

The manure used in this study was sourced from local farms. This approach to soil fertility management is integrated with local conditions, improves food security and environmental sustainability of agricultural systems, and maximizes crop yields while minimizing the exploitation of soil nutrient reserves and degradation of soil physical and chemical properties. The goals of high and stable yield, quality improvement and sustainable development of hickory orchard were realized.

5. Conclusions

In this study, combined organic and chemical fertilizer treatments significantly enhanced the pecans yield and improved the quality compared with the application of only chemical fertilizers. Moreover, this mixed fertilizer approach significantly increased soil nutrient levels and soil enzyme activities. Based on these findings, we recommend the use of various organic fertilizers in conjunction with chemical fertilizers in orchards to enhance the utilization of nutrients, improve soil quality, and increase crop productivity.

Author Contributions: C.F. and S.F.: conceptualization. Y.T. and Z.W.: writing of the manuscript and preparation of figures; data curation, D.G.; writing—review and editing, X.M. (Xiaoxiang Ma) and X.M. (Xiaomin Ma): visualization, C.H.; project administration, F.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Special Major Science and Technology Project of Anhui Province (202103a06020007), the Forestry Science and Technology Promotion Demonstration Project of State (wan 2023TG22), the Science and Technology Project of Anhui Province (GJ2022QN14) and the Huzhou Natural Science Foundation Project (2022YZ19).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author. The data are not publicly available due to compliance with data protection regulations.

Acknowledgments: We thank Xiang Ge (Fuyang harvest agricultural planting professional cooperative), Duxin Gong, Cheng Huang, Xiaomin Ma, Xiaoxiang Ma, Feiyang Yuan, (Anhui Agricultural University), Zhaocheng Wang, (Anhui Agricultural University; Huzhou vocational & technical college) for their support in the collection of field data.

Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

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