

Article

Litter Decomposition of Two Kiwifruit Cultivars ('Jinkui' and 'Hort-16A') with Different Litter Qualities in the Orchard Ecosystem

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Abstract: The aim of this study was to reveal the decomposition differences of kiwifruit litters with different qualities and verify the “Initial Litter Quality Hypothesis”. This study took litters of ‘Jinkui’ and ‘Hort-16A’ kiwifruit as the research objects, and carried out in situ decomposition experiments. The decomposition rate, nutrients release process, and soil enzyme activities were analyzed. In this study, the litter of ‘Hort-16A’ kiwifruit decomposed faster than the litter of ‘Jinkui’ kiwifruit. The decomposition time was positively correlated with the initial concentration of C of the litters, but negatively correlated with the concentrations of N and P. Except for P and Mn, the dynamic trends of the nutrient concentrations were similar during the litter decomposition of ‘Jinkui’ and ‘Hort-16A’ kiwifruit. After 180 days of decomposition, about 85%~95% of the initial concentrations of the macro-elements of the ‘Hort-16A’ kiwifruit litter were released. The dynamic trends of protease activities were similar, but that of sucrase, β -1,4-glucosidase, polyphenol oxidase, and phosphatase were different. In conclusion, the litter quality of kiwifruit affects the decomposition rate, and the difference in decomposition rate in turn affects the dynamic processes of nutrient release and soil enzyme activity. This study provides evidence for the “Initial Litter Quality Hypothesis” in the orchard ecosystem.

Keywords: litter quality; kiwifruit; decomposition process; nutrients; soil enzymes



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1. Introduction

Kiwifruit (*Actinidia*) is widely loved by consumers all over the world because of its unique flavor and rich nutrition [1]. China is the largest producer and consumer of kiwifruit [2]. New Zealand has a suitable environmental condition for kiwifruit growth, excellent cultivars, and a mature management and marketing system, so that it has occupied a leading position in the international market [3].

‘Jinkui’ kiwifruit is a green-flesh cultivar bred in China, which is a large single fruit that has high yield, storage tolerance, and strong resistance, and is widely cultivated in many regions of China [4,5]. ‘Hort-16A’ kiwifruit is a yellow-flesh cultivar bred in New Zealand, which has the advantages of sweet flavor and high nutritional value, and occupies an important share in the international high-end market [6,7]. In recent years, ‘Hort-16A’ kiwifruit has been gradually promoted and cultivated in China. Furthermore, the cultivated areas of ‘Jinkui’ and ‘Hort-16A’ kiwifruit overlap, such as Jiangxi, Sichuan, and Guizhou provinces (Southern China). However, the growth traits and phenology of these two cultivars are different, and the corresponding orchard management measures are also different.

Pruning is a common management measure in kiwifruit orchards [8,9]. By pruning branches and leaves, the excellent mother branches are selected and remain, the structure of the fruit tree is improved, and the high yield of orchards is sustained. Pruned leaves are placed on the surface of the soil and together with naturally falling leaves form the

litter layer in the orchard [10]. In agroforestry systems, litter decomposition is a significant research issue. Sofo et al. [11] reported that the decomposition of pruning residues increased the macrofauna abundance and organic carbon levels in the soils of olive orchards. The enhanced litter decomposition of apples reduced the prevalence of apple scab [12]. In other plantations, such as coffee and tea, the decomposition of leaf litter provided an amount of nutrients to the soil and improved the soil quality [13–16]. Therefore, litter decomposition is an important supplement for orchard soil fertility. However, for these two different kiwifruit cultivars ('Jinkui' and 'Hort-16A'), their litter decomposition processes and the impacts on the soil environment are not clear. This is a factor that cannot be ignored that affects the orchard management.

Under the same climatic conditions, the initial concentrations of lignin, N, and P in litters are the main factors affecting the decomposition rate [17,18]. The high concentrations of N and P in litters provide sufficient nutrients for decomposer activities, leading to faster litter decomposition rates. Lignin is a substance that is difficult to decompose. Lignin can only be decomposed by fungi and its decomposition rate is very slow. Therefore, the high concentration of lignin leads to slower decomposition of litter [19].

During the decomposition process, the litter first covers the surface soil, and then releases nutrients into the surrounding environment through leaching and degradation by decomposers, eventually forming humus and becoming a part of the soil [20]. This process has multiple effects on the physical, chemical, and biological properties of the soil. In the early stage of decomposition, litter, as a soil cover, can effectively maintain water and soil, reduce soil erosion, affect soil temperature and bulk density, and improve soil aggregate stability [10]. As organic matter degrades, nutrient elements are released into the soil, water, or atmosphere. In addition, there are increases in the concentrations of some elements during litter decomposition, such as N, P, and Fe [21]. The decomposers (soil fauna and microorganisms) are the main participants in the litter decomposition process, and bacteria and fungi secrete extracellular enzymes to assist the litter decomposition [22,23]. Moreover, the activities of soil enzymes are different in different stages of decomposition. For example, starch hydrolases tend to have higher activities in the early stage of decomposition, while ligninolytic enzymes have higher activities in the late stage.

Wickings et al. [24] proposed the "Initial Litter Quality Hypothesis", which suggested that the initial quality affected the entire decomposition process of litter, especially its chemical composition. For different cultivars of kiwifruit, the initial litter quality may be different, which could affect the decomposition rate. Furthermore, different decomposition processes affect the orchard soil environment through nutrient release and soil enzyme activity. Here, we propose a hypothesis: the litter quality of kiwifruit affects the decomposition process. In this study, we took the litters of 'Jinkui' and 'Hort-16A' kiwifruit as the research objects. Furthermore, the decomposition rate, release processes of nutrients, and dynamics of soil enzyme activities were analyzed. In addition, the nutrient release and its equivalent fertilizer amount were calculated. This study could provide a reference for management measures such as pruning and fertilization in kiwifruit orchards.

2. Materials and Methods

2.1. Study Site and Species

The study site was Kiwifruit Industry Base of Jiangxi Academy of Sciences (N 28°40'36", E 115°19'02"). This base was a 10-year-old kiwifruit orchard. The area was about 15 hm². The orchard was located in Fengxin County, Southeast China. A number of kiwifruit cultivars including 'Jinkui' and 'Hort-16A' were planted in the orchard. The layout of the orchard is shown in Figure 1a. The climate type in this region was subtropical monsoon climate. During the research period (2021), the temperature was relatively high from May to September, and there was more precipitation from May to June (Figure 1b). The soil type was red soil.

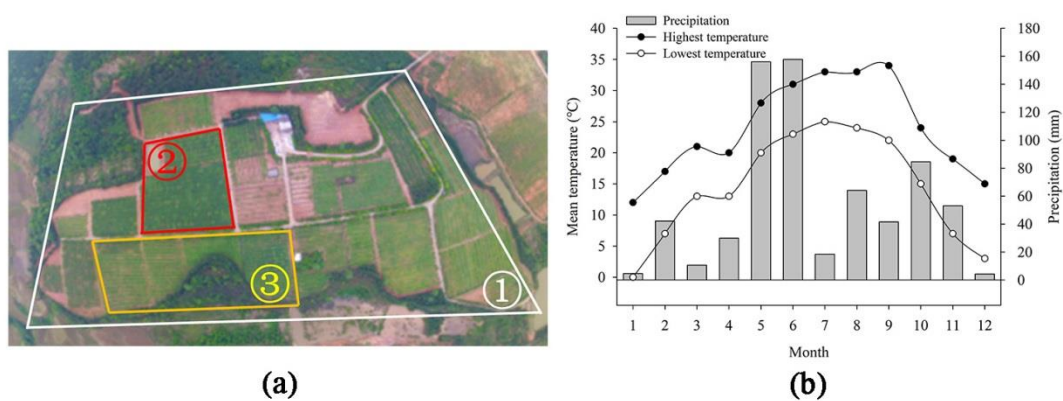


Figure 1. Aerial view and meteorological conditions of the study area in 2021. (a): Aerial view of the orchard. The numbers represent the total area of the orchard (1), the planting area of ‘Jinkui’ kiwifruit (2), and the planting area of ‘Hort-16A’ kiwifruit (3), respectively. (b): Meteorological conditions of the study area in 2021.

In Fengxin County (Jiangxi Province), ‘Jinkui’ and ‘Hort-16A’ kiwifruit are widely cultivated. ‘Jinkui’ kiwifruit is a cultivar bred from the descendants of wild *Actinidi deliciosa* seeds in China. The shape of the fruit is wide oval or cylindrical, with brown pericarp, a hairy surface, and green flesh. Furthermore, the fruit is large, with an average single fruit weight of more than 100 g. It is resistant to storage and has a high resistance to kiwifruit canker. It is planted in Hubei, Jiangxi, Sichuan, Fujian, and other provinces, and it is one of the representative cultivars of green-flesh kiwifruit in China.

‘Hort-16A’ kiwifruit is an *A. chinensis* cultivar bred in New Zealand. The shape of the fruit is prolate cylindrical with a sharp beak. The pericarp is brown, smooth, and hairless. The flesh is golden. Moreover, ‘Hort-16A’ kiwifruit is recognized as an excellent cultivar in the world and plays an important role in the international high-end kiwifruit market. Therefore, it is one of the representative cultivars of golden-flesh kiwifruit. In recent years, it has been gradually promoted and cultivated in China. It is planted in Jiangxi, Sichuan, Guizhou, and other provinces.

For the litter substrate quality of the ‘Jinkui’ kiwifruit, the concentrations of K, Cu, and Zn were higher, and the values of C/N, C/P, and N/P were higher (Table 1). For the litter substrate quality of the ‘Hort-16A’ kiwifruit, the concentrations of N, P, Ca, Mg, Mn, and B were higher. The concentrations of C and Fe of the two litters were similar.

Table 1. Initial nutrient concentrations of litters of ‘Jinkui’ and ‘Hort-16A’ kiwifruit.

Nutrients	Jinkui	Hort-16A	Nutrients	Jinkui	Hort-16A
C (g/kg)	417 ± 23	403 ± 19	Ca (g/kg)	14 ± 2	19 ± 4
N (g/kg)	13.5 ± 2.8	17.9 ± 3.7 *	Mg (g/kg)	2.54 ± 0.30	3.59 ± 0.21
P (g/kg)	2.1 ± 0.2	4.3 ± 0.3 **	Fe (mg/kg)	186 ± 35	196 ± 29
K (g/kg)	14.8 ± 1.5 **	5.3 ± 0.6	Mn (mg/kg)	318 ± 21	357 ± 32
C/N	30.89 ± 4.52 *	22.51 ± 4.58	Cu (mg/kg)	20.5 ± 2.8	18.7 ± 2.3
C/P	198.57 ± 25.36 **	93.72 ± 10.29	Zn (mg/kg)	21.0 ± 1.5	18.5 ± 2.0
N/P	6.43 ± 0.92	4.16 ± 1.08	B (mg/kg)	20.5 ± 2.2	32.6 ± 3.5 *

*, $p < 0.05$; **, $p < 0.01$.

2.2. Litter Decomposition Study

The field study was performed in the kiwifruit orchard. Trees of ‘Jinkui’ and ‘Hort-16A’ kiwifruit were planted in 2015 with a distance of 4 m between tree rows and 3 m between trees within one row. An average of 825 fruit trees were planted per hectare. In December of each year, the trees were pruned and the pruned branches and leaves were covered on the soil surface. Fertilization began in February of the following year, with 2.25 t of organic fertilizer, 150 kg of $\text{Ca}(\text{H}_2\text{PO}_4)_2$, 75 kg of urea, and 75 kg of K_2SO_4 applied per

hectare. Fertilizer was applied once in May and once in October, and the total amount of fertilizer applied was about equal to that applied in February. Irrigation depended on the precipitation situation and a soil field capacity of over 60% was maintained.

The decomposition of the kiwifruit litter was studied using the litter bag method. Five 5 m × 5 m study plots were established in the planting areas of the ‘Jinkui’ and ‘Hort-16A’ kiwifruit, respectively. In each plot, we analyzed the soil’s physical and chemical properties, and the results are shown in Table S1. There was no significant difference in the concentrations of C, N, P, and K in the soils between the orchards of the ‘Jinkui’ and ‘Hort-16A’ kiwifruit. The pH values of the soil in the ‘Jinkui’ and ‘Hort-16A’ kiwifruit orchards were 5.71 and 5.50, respectively, with no significant difference. The pruning time was December 2020. We collected the leaf litter and brought it back to the laboratory. The litter samples were dried for 48 h at 60 °C by the drying oven. We weighed 10.0 g of dried litter samples, and placed them into a nylon mesh bag with a size of 15 cm × 25 cm and a 0.5 mm mesh diameter. A total of 30 litterbags were prepared for the ‘Jinkui’ kiwifruit and ‘Hort-16A’ kiwifruit, respectively. In each plot, we placed and secured six bags on the soil surface on January 2, 2021. During the decomposition experiment, we retrieved the litter bags every 30 days, and we sampled 100 g of surface soil under the bag. The decomposition times of this study were 180 days, and the samples were taken six times. The study period was from 2 January to 30 June 2021.

The retrieved decomposition residue of kiwifruit litter was placed in a 0.15 mm soil sieve to wash off the soil and hypha with water, dried for 48 h at 60 °C, and then weighed. Subsequently, the nutrient concentrations of the residue were determined. According to the methods in Trinsoutrot et al. [25], the concentrations of C and N were determined by the element analyzer (vario MACRO cube, Germany Elementar, Langenselbold, Germany). According to the methods in Lu et al. [26], the concentration of P was determined by the ultraviolet spectrophotometer (UV-1800, Japan Shimadzu, Kyoto, Japan), and the concentration of K was determined by the atomic absorption spectrometer (Analyst 800, USA PE, Cincinnati, OH, USA).

The determination methods of micro-element concentrations refers to Levine et al. [27] and Chevallier et al. [28]. The inductively coupled plasma optical emission spectrometer (ICP-OES) (ICPE-9800, Japan Shimadzu) was used to determine the concentrations of Ca, Mg, Fe, and Mn. The inductively coupled plasma-mass spectrometry (ICP-MS) (ICPMS2030, Japan Shimadzu) was used to determine the concentrations of Cu, Zn, and B.

The soil samples were taken back to the laboratory, and air-dried in the shade after the grits and plant roots were removed. We ground the soil and sifted it with the soil sieve (diameter of 0.25 mm). According to the methods in Lu et al. [26], the activities of soil enzymes were determined by the ultraviolet spectrophotometer (UV-1800, Japan Shimadzu). Specifically, the activities of sucrase were determined by 3,5-dinitrosalicylic acid colorimetry. The activities of β-1,4-glucosidase were determined by nitrophenol colorimetry. The activities of polyphenol oxidase were determined by pyrogalllic acid colorimetry. The activities of protease were determined by ninhydrin colorimetry. The activities of phosphatase were determined by disodium phenyl phosphate colorimetry.

2.3. Data Analysis

The litter decomposition rate was calculated by the Olson’s model (exponential decay model) [26]. This model was fitted based on litter residual rate and decomposition time, and the equation of model was as follows:

$$R = ae^{-bt} + ce^{-dt} \quad (1)$$

where R was the residual rate of litter, a , b , c , and d were the model parameters, e was the natural constant, and t was the decomposition time. We calculated the time when the residual rate of litter was 50%, which was the half-life period ($T_{0.5}$), and also calculated the time when the residual rate of litter was 5%, which was the turnover period ($T_{0.05}$). The SigmaPlot 12.5 software was used for model fitting and calculation.

In addition, the relative return index (*RRI*) was used to measure the proportion of nutrient release after the decomposition [29]. Here was the calculation formula:

$$RRI = (M_0 \times C_0 - M_1 \times C_1) / (M_0 \times C_0) \times 100\% \quad (2)$$

where *RRI* was the relative return index, M_0 was the initial dry matter mass of litter, and M_1 was the final dry matter mass. C_0 was the initial nutrient concentration of litter, and C_1 was the final nutrient concentration.

Based on the initial nutrient concentration and the *RRI* of litters, we calculated the nutrient release and equivalent fertilizer amount. The calculation formulas were as follows:

$$R_1 = (C_0 \times RRI) / 100 \quad (3)$$

$$R_2 = R_1 \times 7.5 \quad (4)$$

$$F_1 = R_2 \times C_f \quad (5)$$

$$F_2 = (F_1 / M_f) \times 100\% \quad (6)$$

where R_1 was the nutrient release for 1 kg of litter, R_2 was the nutrient release in 1 hm^2 of orchard. Based on the studies of Chen et al. [30], 1 hm^2 of kiwifruit orchard could produce 7.5 t of litter. F_1 was the amount of fertilizer converted from the amount of nutrient released. C_f was the concentration of nutrient elements in the fertilizers. The C concentration of organic fertilizer was calculated as 10%, the N concentration of urea was calculated as 46.7%, the P concentration of $\text{Ca}(\text{H}_2\text{PO}_4)_2$ was calculated as 20%, and the K concentration of K_2SO_4 was calculated as 50%. F_2 was the proportion of F_1 to the annual fertilization, and M_f was the annual fertilization of 1 hm^2 of orchard, including 4.5 t of organic fertilizer, 300 kg of $\text{Ca}(\text{H}_2\text{PO}_4)_2$, 150 kg of urea, and 150 kg of K_2SO_4 .

The SPSS 26 software was used to conduct one-way analysis of variance (ANOVA) on the initial quality, nutrient concentration, relative return index, soil enzyme activity, and other data of the litters of 'Jinkui' and 'Hort16A' kiwifruit, so as to test the significance of the differences between different data. We used the least significant difference method (*LSD*, $p < 0.05$) for multiple comparison. Based on the SPSS 26 software, we analyzed the correlation (Pearson correlation coefficient, r) between litter quality and decomposition rate, as well as the correlation between nutrient concentration and soil enzyme activity. Based on the SigmaPlot 12.5 software, we modeled and fitted the correlation between nutrient concentration and soil enzyme activity. All figures were plotted by the SigmaPlot 12.5 software.

3. Results

3.1. Decomposition Model and Rate

Based on the calculation results of the Olson's exponential model, the half-life period of litter decomposition of the 'Jinkui' kiwifruit was 119.4 days, and the turnover period was 594.4 days (Figure 2). The half-life period of litter decomposition of the 'Hort-16A' kiwifruit was 64.1 days, and the turnover period was 266.1 days. The litter decomposition rate of the 'Hort-16A' kiwifruit was significantly faster, and the decomposition rate of the 'Jinkui' kiwifruit was relatively slower.

We analyzed the correlation between the initial nutrient concentration and decomposition rate of the kiwifruit litter. The results showed that the C concentration and C/N ratio were positively correlated with the half-life period (Figure 3). The concentrations of N, P, and B were negatively correlated with the half-life period. Moreover, the C concentration and C/P ratio were positively correlated with the turnover period. The concentrations of P and B were negatively correlated with the turnover period.

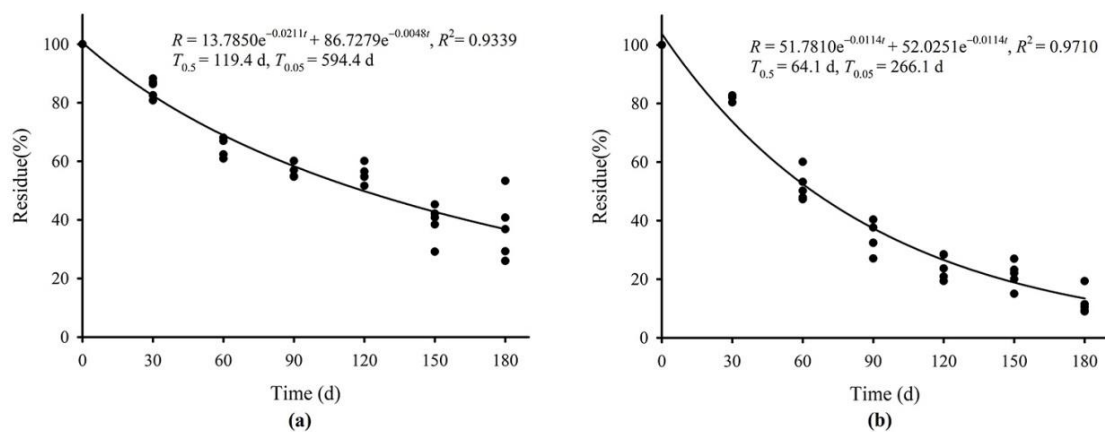


Figure 2. Litter decomposition rate of 'Jinkui' and 'Hort-16A' kiwifruit. (a): 'Jinkui' kiwifruit. (b): 'Hort-16A' kiwifruit.

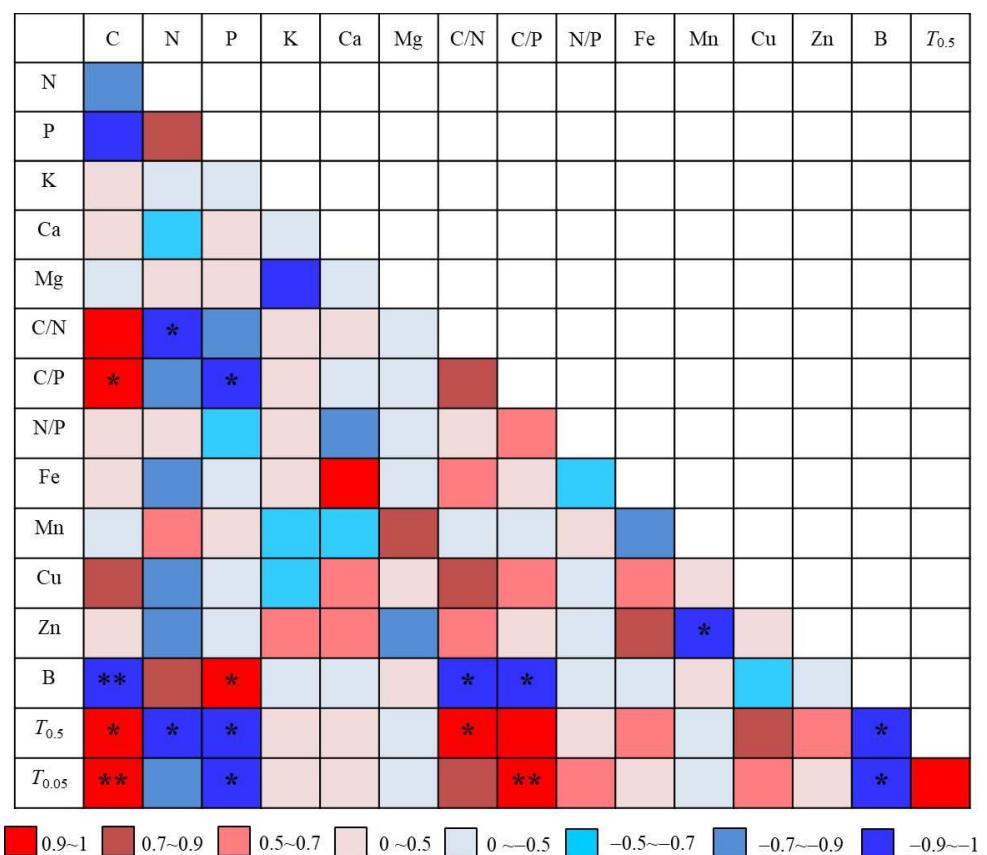


Figure 3. Correlations between initial nutrient concentration and decomposition rate of kiwifruit litter. Red represents a positive correlation, blue represents a negative correlation. The darker the color represents the stronger the correlation. *: $p < 0.05$; **: $p < 0.01$.

3.2. Dynamic Trend of Nutrients in the Decomposition Process

In the decomposition process of the kiwifruit litter, the dynamics of the concentrations of C, N, K, Ca, and Mg were similar, but that of the P concentration was different (Figure 4). Specifically, the C concentration of the two litters showed a decreasing trend. The N concentration of the 'Jinkui' kiwifruit showed an increasing trend. The N concentration of the 'Hort-16A' kiwifruit increased at the first 120 days of the experiment, after that, it showed a decreasing trend. The P concentration of the 'Jinkui' kiwifruit was relatively stable at 2.0 g/kg, while that of the 'Hort-16A' kiwifruit was gradually decreasing. The

K concentration decreased at the first 60 days, after that, it remained relatively stable at 0.5 g/kg. The Ca concentration of the two litters increased at the first 60–90 days and then decreased. The Mg concentration of the two litters increased at the first 30 days and then decreased. Moreover, during litter decomposition, the value of the C and Mg concentrations of the ‘Jinkui’ kiwifruit were higher than that of the ‘Hort-16A’ kiwifruit. The values of the N, P, and Ca concentrations of the ‘Hort-16A’ kiwifruit were higher than that of the ‘Jinkui’ kiwifruit.

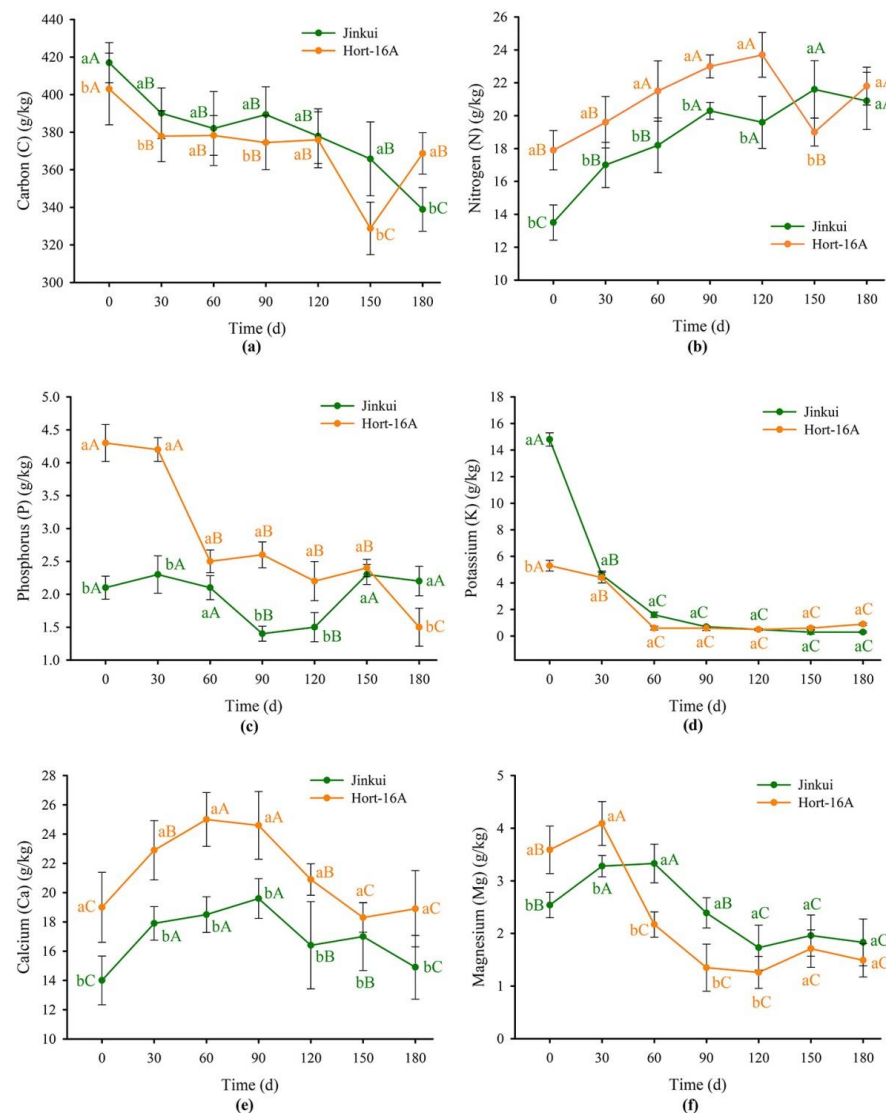


Figure 4. Dynamics of macro-elements during kiwifruit litter decomposition. (a): Dynamics of C concentrations; (b): dynamics of N concentrations; (c): dynamics of P concentrations; (d): dynamics of K concentrations; (e): dynamics of Ca concentrations; (f): dynamics of Mg concentrations. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in cultivars ($p < 0.05$).

For the micro-elements of the litters of ‘Jinkui’ and ‘Hort-16A’ kiwifruit, the dynamic trends of Fe, Cu, Zn and B concentrations were similar, but that of the Mn concentration was different (Figure 5). More precisely, the concentrations of Fe, Cu, and Zn showed an increasing trend. The Mn concentration of the ‘Jinkui’ kiwifruit increased at the first 120 days, after that, it fluctuated. The Mn concentration of the ‘Hort-16A’ kiwifruit remained relatively stable at 300 mg/kg. The B concentrations of the two litters increased at the first 30–60 days and then decreased gradually. Moreover, the value of the Mn concentration of the ‘Jinkui’

kiwifruit was higher than that of the ‘Hort-16A’ kiwifruit. The values of the Fe, Cu, and Zn concentrations of the ‘Hort-16A’ kiwifruit were higher than that of the ‘Jinkui’ kiwifruit.

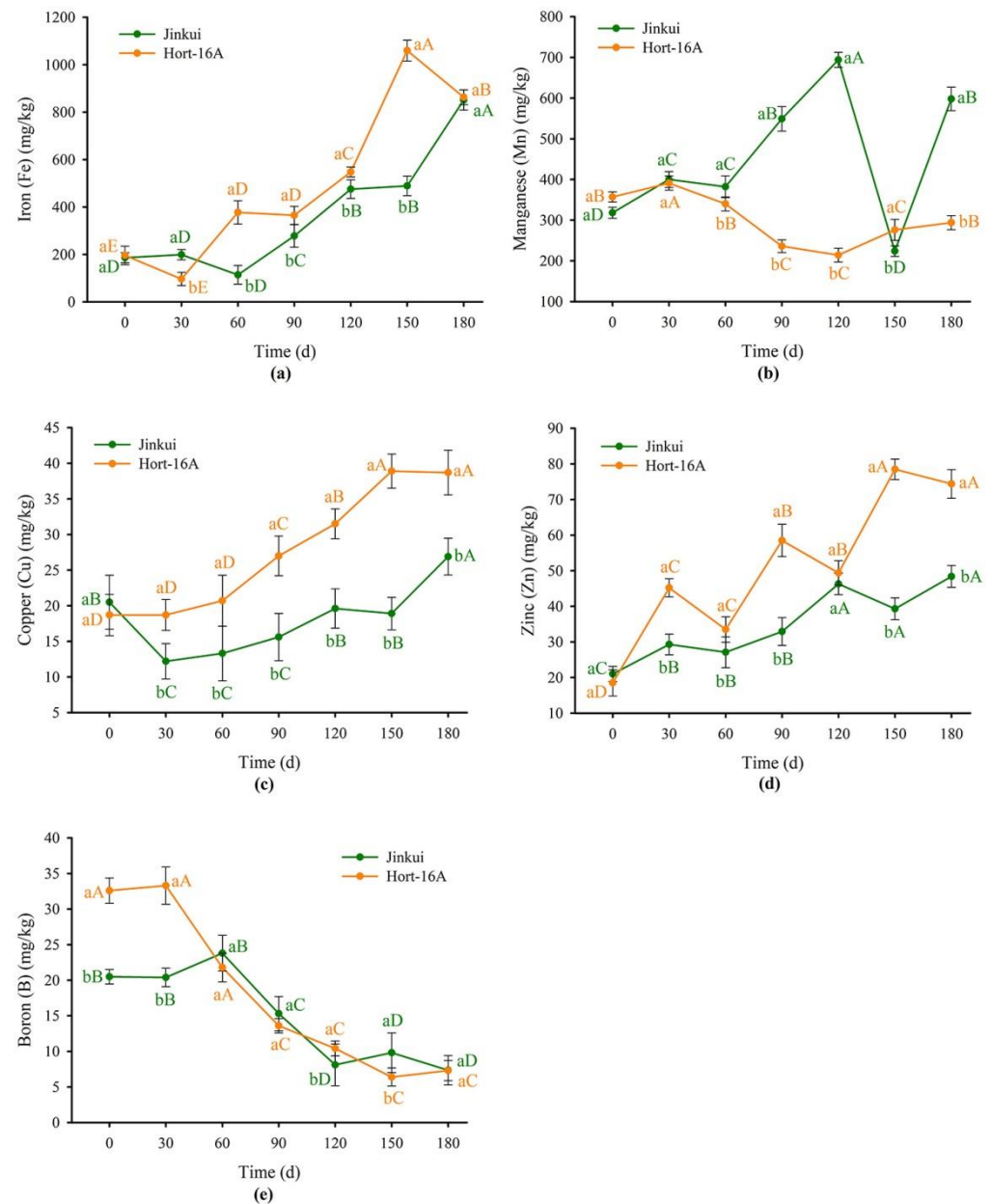


Figure 5. Dynamics of micro-elements during kiwifruit litter decomposition. (a): Dynamics of Fe concentrations; (b): dynamics of Mn concentrations; (c): dynamics of Cu concentrations; (d): dynamics of Zn concentrations; (e): dynamics of B concentrations. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in cultivars ($p < 0.05$).

After 180 days of decomposition, about 85%~95% of the initial concentrations of the macro-elements of the ‘Hort-16A’ kiwifruit litter were released (Figure 6). The relative return indexes (release proportions) of the macro-elements of the ‘Jinkui’ kiwifruit litter were relatively lower. For the litter of the ‘Jinkui’ kiwifruit, 60%~70% of the initial concentrations of C, P, Ca, and Mg, 42% of the initial concentration of N, and 99% of the initial concentration of K were released. The relative return indexes of the micro-elements of the two litters were significantly different. For the litter of the ‘Hort-16A’ kiwifruit, more than 75% of the initial concentrations of Mn, Cu, and B, and about 50% of the initial concentrations of Fe

and Zn were released. For the litter of ‘Jinkui’ kiwifruit, 30% of the initial concentration of Mn, 51% of the initial concentration of Cu, 14% of the initial concentration of Zn, and 87% of the initial concentration of B were released. In addition, 70% of the initial concentration of Fe was enriched.

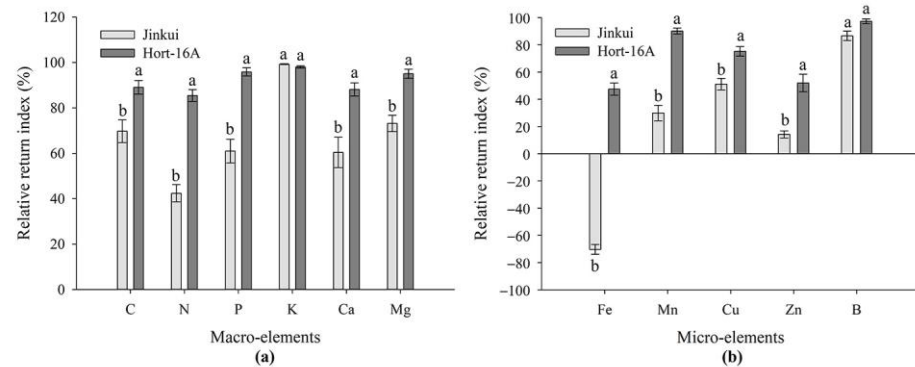


Figure 6. Relative return index during kiwifruit litter decomposition. (a): The relative return indexes of macro-elements; (b): the relative return indexes of micro-elements. Different lowercase letters indicate significant differences in cultivars ($p < 0.05$).

The conversion results showed that more than 210 kg of C could be released from the litter of the kiwifruit orchard per hectare during the decomposition experiments, which was approximately equivalent to 50% of the annual organic fertilizer application (Table 2). Moreover, about 4–11 kg of N could be released from the litter of the orchard per hectare, which was approximately equivalent to 6–16% of the annual urea application. About 3–11 kg of K could be released from the litter of the orchard per hectare, which was approximately equivalent to 5–14% of the annual K_2SO_4 application. The release of P was relatively small, accounting for less than 6% of the annual $Ca(H_2PO_4)_2$ application. It must be emphasized that this was only an estimation result but could be a reference for fertilization in kiwifruit orchards.

Table 2. Releases of nutrient elements and fertilizer conversion after 180 days of decomposition experiments.

Elements	Release of 1 kg of Litter (g)		Release of 1 hm ² of Orchard (kg)		Fertilizers	Converted to Fertilizer (kg)		Proportion of Annual Fertilization (%)	
	Jinkui	Hort-16A	Jinkui	Hort-16A		Jinkui	Hort-16A	Jinkui	Hort-16A
C	29.08	35.90	218.14	269.26	Organic fertilizer	2181.36	2692.61	48.47	59.84
N	0.57	1.53	4.29	11.47	Urea	9.19	24.57	6.12	16.38
P	0.13	0.41	0.96	3.09	$Ca(H_2PO_4)_2$	4.80	15.45	1.60	5.15
K	1.47	0.52	11.02	3.89	K_2SO_4	22.03	7.79	14.69	5.19

3.3. Dynamic Trend of Soil Enzyme Activity in the Decomposition Process

In the decomposition process of the kiwifruit litter, the dynamic trends of protease activities were similar, but that of sucrase, β -1,4-glucosidase, polyphenol oxidase, and phosphatase were different (Figure 7). Specifically, the protease activities increased at the early stage and then decreased. The sucrase activity of the ‘Jinkui’ kiwifruit increased in the first 60 days; after that, it decreased gradually. The sucrase activity of the ‘Hort-16A’ kiwifruit remained relatively stable, except for a dip on the 90th day. The β -1,4-glucosidase activity of the ‘Jinkui’ kiwifruit increased in the first 120 days; after that, it decreased gradually. The activity of the ‘Hort-16A’ kiwifruit showed a gradual increase trend. For the polyphenol oxidase of the ‘Jinkui’ kiwifruit litter, the activity showed a gradual increase trend. For the polyphenol oxidase of the ‘Hort-16A’ kiwifruit litter, the activity showed a relatively stable trend. For the phosphatase of the ‘Jinkui’ kiwifruit litter, the activity

increased in the first 60 days; after that, it remained relatively stable. For the phosphatase of the ‘Hort-16A’ kiwifruit litter, the activity showed a relatively stable trend.

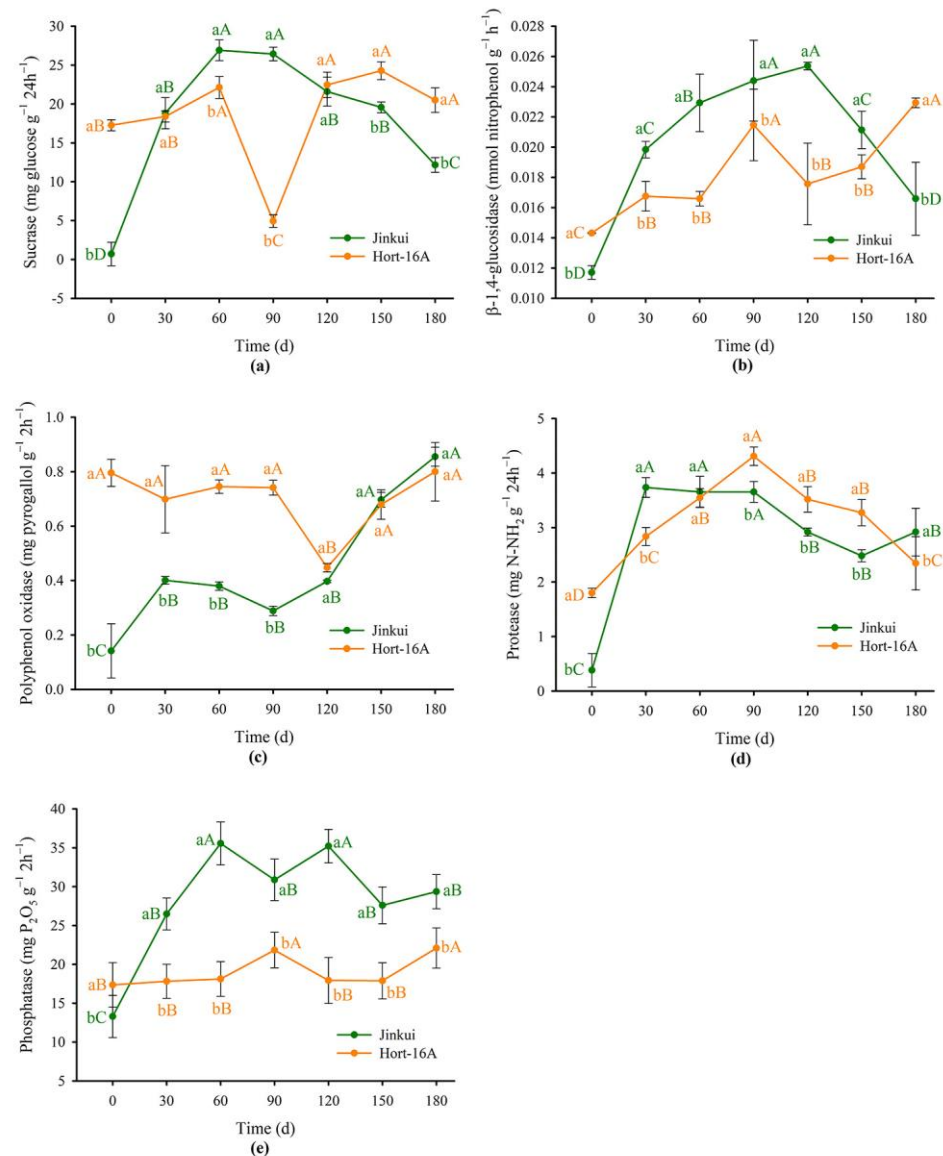


Figure 7. Dynamic trend of soil enzyme activity in the decomposition process of kiwifruit litter. (a): Sucrase; (b): β -1,4-glucosidase; (c): polyphenol oxidase; (d): protease; (e): phosphatase. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in cultivars ($p < 0.05$).

3.4. Relationship between Nutrient Concentration and Soil Enzyme Activity during Litter Decomposition

The relationship between the N concentration and protease activity was positively correlated (Pearson correlation coefficient, $r = 0.604$, $p < 0.05$) (Figure 8). Moreover, the relationship between the N concentration and polyphenol oxidase activity was positively correlated ($r = 0.539$, $p < 0.05$). The relationship between the Ca concentration and protease activity was positively correlated ($r = 0.586$, $p < 0.05$). The relationship between the Mn concentration and phosphatase activity was positively correlated ($r = 0.628$, $p < 0.05$).

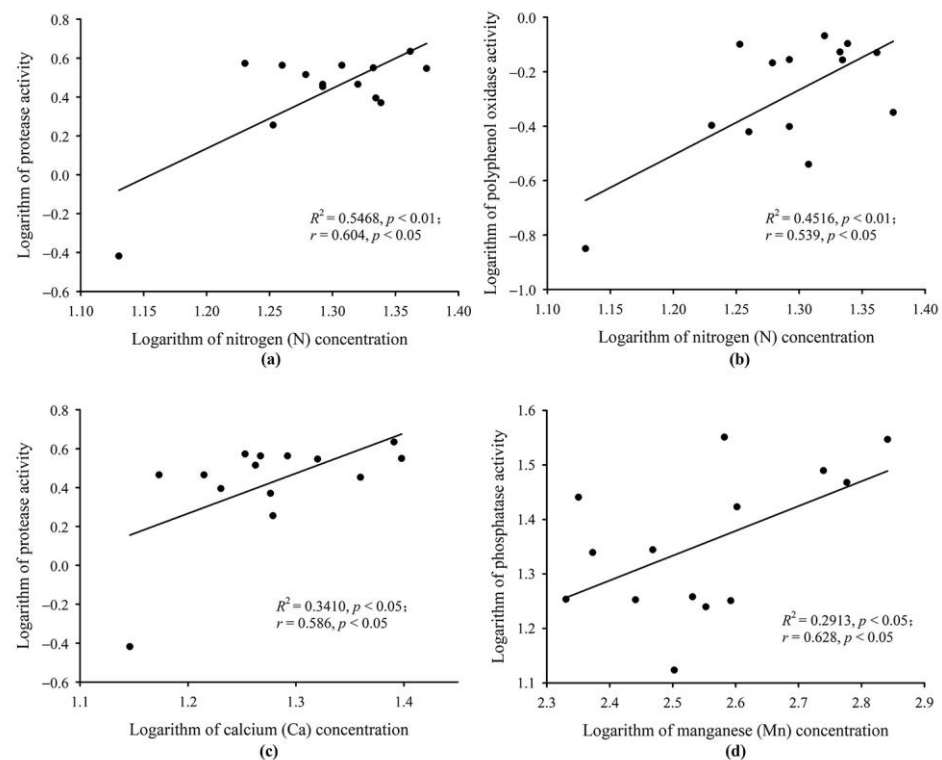


Figure 8. Relationship between nutrient concentration and soil enzyme activity in the process of litter decomposition. (a): N and protease; (b): N and polyphenol oxidase; (c): Ca and protease; (d) Mn and phosphatase.

4. Discussion

4.1. Decomposition Rate and Litter Quality

Litter quality is an indicator to measure the initial state of litters, which mainly includes the nutrient concentrations, structural compounds, and secondary metabolites in litters [31]. Based on the “Initial Litter Quality Hypothesis”, the whole process of litter decomposition is continuously affected by the initial litter quality [24]. Specifically, a litter with a high concentration of nutrients and a low concentration of lignin and polyphenols decomposes faster. In this study, the litter of ‘Hort16A’ kiwifruit decomposed faster. Correspondingly, for the litter substrate quality of the ‘Hort-16A’ kiwifruit, the initial concentrations of N and P were higher, and the values of C/N and C/P were lower. Moreover, the decomposition rate was significantly correlated with the initial concentrations of C and P, followed by the initial concentration of N, which mainly affected the early stage of decomposition. Therefore, these results could support the “Initial Litter Quality Hypothesis”.

In the litter decomposition, N and P are the important factors affecting the compositions and activities of microbial communities and extracellular enzymes [32]. Previous research showed that litters with a high N concentration were more accessible by microbial colonization [31,33]. The hypha growth, spore production, and extracellular enzyme synthesis of fungi all require a large amount of input of N [33]. P is an essential element for DNA replication and transcription, so it is also a limiting element for the abundance of bacterial and fungal communities [34]. Furthermore, P is a rate-limiting factor in the synthesis of extracellular enzymes, such as phosphatase and cellulolytic enzymes [34]. Thus, litters with a high concentration of N and P tend to decompose faster. In other words, the concentrations of N and P are negatively correlated with the time of litter decomposition, which was verified in the results of this study. The litter of ‘Hort-16A’ kiwifruit had the higher initial concentrations of N and P, and its decomposition rate was faster.

In litters, the C concentration reflects the content of carbon-containing compounds, which are mainly lignin, cellulose, and hemicellulose [17]. In the early stage of litter decomposition, the mass loss is less than 40%, mainly the degradation of cellulose and hemicellulose. When the mass loss is over 40%, which is the later stage, it is mainly the degradation of lignin [35]. Lignin has a negative effect on litter decomposition. First, lignin is a stubborn aromatic matrix that is difficult to decompose and can only be degraded by specific microorganisms and enzymes, such as *Basidiomycota*, manganese peroxidase, and laccase [36,37]. Moreover, lignin is not a suitable C source for decomposers, because more C is required for the synthesis of related degrading enzymes. Second, lignin participates in cell wall formation, improves the strength and rigidity of plant tissues, and binds to polysaccharide fibers to inhibit the degradation of cellulose and hemicellulose [34,38]. Finally, a high lignin concentration means the relatively low concentrations of N and P, that is to say, the high C/N ratio and C/P ratio. Without sufficient nutrient support, the diversity and activity of the microbial community is low. Therefore, the higher the values of the C concentration, C/N ratio, and C/P ratio, the longer the decomposition time [39,40], which were consistent with our results. With the higher values of the C/N ratio and C/P ratio, the litter decomposition rate of the 'Jinkui' kiwifruit was slower.

4.2. Litter Quality and the Dynamics of Nutrients

In addition to the decomposition rate, the dynamics of nutrients were also influenced by the litter quality [41,42]. In terms of direct effects, due to the higher initial concentration, the concentrations of N, P, and Ca were higher in the 'Hort16A' kiwifruit litter during decomposition. Furthermore, N is a component of protein, P is a component of genetic material, and Ca is a constituent of fungal cell walls [43]. The three elements are essential nutrients to maintain the growth and metabolism of a microbial decomposer [44]. In terms of indirect effects, with the higher litter quality (lower C/N ratio and C/P ratio) and faster decomposition rate, the 'Hort16A' kiwifruit litter lost more dry matter than the 'Jinkui' kiwifruit litter during the decomposition experiment. Correspondingly, the 'Hort16A' kiwifruit litter released more nutrients, including C, N, P, Ca, Mg, Fe, Mn, Cu, and Zn. However, litter quality is not the only factor determining the dynamics of nutrients. Even if the initial concentration was similar, there were differences in the dynamics of the nutrients, mainly reflected in the dynamics of Fe, Mn, Cu, and Zn. The reason is that nutrient dynamics are also affected by the element's chemical characteristics, decomposition process, and microenvironment [41]. Moreover, the dynamics of Fe, Cu, and Zn were all rising, and the increase in metallic elements concentration has been observed in many previous studies [41,45]. The potential mechanism may be that the metal elements form chelates or complexes with humic acids [46]. With a faster decomposition rate and humification process, more chelates and complexes were formed, resulting in higher concentrations of Fe, Cu, and Zn in the 'Hort16A' kiwifruit litter. For the dynamic of Mn in the 'Jinkui' kiwifruit litter, there was a significant upward trend after 60 days of the decomposition experiment, and the concentration of Mn was higher. Mn is a component of manganese peroxidase, and its function is to decompose lignin and humification products [47,48]. The degradation of lignin mainly occurred at the later stage of decomposition, when the fungi recruit Mn from the environment to synthesize related decomposition enzymes, leading to an increase in Mn concentration in the litter [21,49].

During litter decomposition, nutrient release is also a process of nutrient mineralization [15]. Under the action of microorganisms, C and N in litter are converted from organic to inorganic and retained in soil and water. In addition, a portion of C will be released into the atmosphere as gases such as CO₂ [20]. Based on previous studies, the mineralization rate of soil N was positively correlated with the litter decomposition rate [50,51]. With a faster decomposition rate, the mineralization rate of N in the soil of the 'Hort16A' kiwifruit orchards may be faster, which provides more nutrient sources for the growth of fruit trees. Combined with the litter decomposition process, N mineralization mainly occurs from March to April, which is the period of nutrient demand for fruit tree growth, so there is

no problem with plant nutrient acceptance. However, soil nutrient mineralization is also affected by rain leaching [52,53], so it is crucial to prevent soil erosion in orchards. Of course, litter mulching is also one of the ways to prevent soil erosion and fertility loss [10].

4.3. Litter Quality and Soil Enzyme Activities

In the process of litter decomposition, soil enzymes assist microorganisms in the degradation of organic matter and the transport of nutrient elements [54]. The activities of soil enzymes are mainly affected by the soil environment (such as temperature, moisture, and nutrient availability) and litter quality [55–57]. The effect of litter quality on enzyme activity is reflected in the control of the decomposition process [58]. In the decomposition stage dominated by degradation of glucoside and cellobiose, the activity of hydrolase increases, while in the decomposition stage dominated by degradation of lignin, the activity of oxidase increases. The decomposition stage is affected by the C/N ratio of litters. Tian and Shi [22] found that litters with a low C/N ratio promoted hydrolase activity, while litters with a high C/N ratio promoted oxidase activity. For the ‘Hort16A’ kiwifruit litter, the C/N ratio was low, so the degradation of glucoside and cellulose was the dominant process during the decomposition experiment. The activities of sucrase and β -1,4-glucosidase showed an increased trend, while the activities of polyphenol oxidase remained stable. For the ‘Jinkui’ kiwifruit litter, the C/N ratio was relatively high. The 90th–120th day of the decomposition experiment was a transitional period. Before the transitional period, the degradation of glucoside and cellulose was the dominant process, and the hydrolases activities (sucrase and β -1,4-glucosidase) increased. After the transitional period, the degradation of lignin was the dominant process, and the hydrolases activities decreased, while the oxidases activities (polyphenol oxidase) increased.

Proteases participate in the transformation of nitrogen-containing organic compounds (such as amino acids and proteins) in soil by hydrolyzing protein peptide chains. During the litter decomposition of kiwifruit, the enrichment of N corresponded to the increase in protease activity. Correspondingly, the relationship between N concentration and protease activity was positively correlated. However, the impact of N on soil enzyme activity is various, and goes far beyond proteases. Ge et al. [55] reported that the litter N concentration was positively correlated with polyphenol oxidase and peroxidase in soil. The positive correlation between N and polyphenol oxidase was also found in this study, and the reason may be that microorganisms synthesized polyphenol oxidase to utilize N compounds that were bound or blocked by stubborn organic substances [22]. The function of phosphatase is to convert organic phosphorus into phosphate for absorption by microorganisms [56]. During litter decomposition of the ‘Jinkui’ kiwifruit, the concentration of P was low, and microorganisms needed to obtain P from the soil to meet their own life activities, resulting in an increase in phosphatase activity. During litter decomposition of the ‘Hort16A’ kiwifruit, the initial concentration of P was high and gradually decreased, and microorganisms were not limited by P. Therefore, the phosphatase activity remained low. In addition, our results showed that the Mn concentrations was positively correlated with the phosphatase activity, which was consistent with the research results from Wu et al. [59]. Based on the litter decomposition experiment in subtropical plantations of southern China, Mn addition increased the soil phosphatase activities.

It is worth noting that soil enzymes are the medium released by microorganisms to degrade litter [54]. Soil microorganisms, mainly fungi and bacteria, are the main participants in the decomposition process [20]. On the one hand, the nutrients in litters are important energy sources for microorganisms, so the decomposition process of litters will inevitably affect microbial communities. For example, Zhang et al. [60] reported that the straw residual rate was positively correlated with microbial species richness and evenness in a peach orchard. On the other hand, the microorganisms mineralize or immobilize the nutrients depending on their demands during the decomposition process. In addition, based on the research results of tea and sugarcane, there were differences in the structure of rhizosphere microorganisms among different varieties of plants [61]. In this study, there

may be differences in the rhizosphere microorganisms between the ‘Jinkui’ and ‘Hort16-A’ kiwifruit; whether it will affect the decomposition process of litter requires further verification. Therefore, microbial activity is an important issue in the study of kiwifruit litter decomposition, and it is also one of our further research directions.

5. Conclusions

Our results confirmed that there were differences in the litter quality among different cultivars of kiwifruit, which led to differences in the decomposition process. This verifies our initial hypothesis: the litter quality of kiwifruit affects the decomposition process. Specifically, the litter quality of kiwifruit affects the decomposition rate, and the difference in the decomposition rate in turn affects the dynamic process of nutrient release and soil enzyme activity. This study also provides evidence for the “Initial Litter Quality Hypothesis” in orchard ecosystems. It is worth emphasizing that the effect of litter quality on the decomposition process also includes indirect effects, achieved by regulating microbial communities and soil enzyme activities.

With the high initial quality (lower C/N ratio and C/P ratio), the litter of ‘Hort16A’ kiwifruit released about 85%~95% of the initial concentrations of the macro-elements and more than 50% of the micro-elements. After conversion, more than 200 kg of C and 10 kg of N could be released from the litter of the kiwifruit orchard per hectare during the decomposition experiments. It was an important supplement to the soil fertility of the orchard. By contrast, with the higher C/N ratio and C/P ratio, the initial quality of the ‘Jinkui’ kiwifruit litter was low. Moreover, its decomposition rate was slow, and the decomposition process was limited by N and P. Therefore, an appropriate addition of nitrogen and phosphorus fertilizers could promote the decomposition of ‘Jinkui’ kiwifruit litter. In addition, 70% of the initial concentration of Fe was enriched during decomposition of the ‘Jinkui’ kiwifruit litter. Thus, it is necessary to consider supplementing iron fertilizer according to soil fertility in the ‘Jinkui’ kiwifruit orchard. This study could provide references for management measures such as pruning and fertilization in kiwifruit or other orchards.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture13101968/s1>, Table S1: Physicochemical characterization of the soil of kiwifruit orchard.

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References

1. Wang, S.; Qiu, Y.; Zhu, F. Kiwifruit (*Actinidia* spp.): A review of chemical diversity and biological activities. *Food Chem.* **2021**, *350*, 128469. [\[CrossRef\]](#)
2. Guo, J.; Yuan, Y.; Dou, P.; Yue, T. Multivariate statistical analysis of the polyphenolic constituents in kiwifruit juices to trace fruit varieties and geographical origins. *Food Chem.* **2017**, *232*, 552–559. [\[CrossRef\]](#)
3. Tait, A.; Paul, V.; Sood, A.; Mowat, A. Potential impact of climate change on Hayward kiwifruit production viability in New Zealand. *N. Z. J. Crop Hortic. Sci.* **2018**, *46*, 175–197. [\[CrossRef\]](#)
4. Ferguson, A.R. Chapter Two—Kiwifruit: The Wild and the Cultivated Plants. In *Advances in Food and Nutrition Research*; Boland, M., Moughan, P.J., Eds.; Academic Press: Cambridge, MA, USA, 2013; Volume 68, pp. 15–32.
5. Huang, H.; Ferguson, A.R. Review: Kiwifruit in China. *N. Z. J. Crop Hortic. Sci.* **2001**, *29*, 1–14. [\[CrossRef\]](#)

6. Richardson, A.C.; Boldingh, H.L.; McAtee, P.A.; Gunaseelan, K.; Luo, Z.; Atkinson, R.G.; David, K.M.; Burdon, J.N.; Schaffer, R.J. Fruit development of the diploid kiwifruit, *Actinidia chinensis* ‘Hort16A’. *BMC Plant Biol.* **2011**, *11*, 182. [\[CrossRef\]](#)
7. Patterson, K.; Burdon, J.; Lallu, N. ‘HORT16A’ kiwifruit: Progress and issues with commercialisation. *Acta Hortic.* **2003**, *610*, 267–273. [\[CrossRef\]](#)
8. Miller, S.A.; Broom, F.D.; Thorp, T.G.; Barnett, A.M. Effects of leader pruning on vine architecture, productivity and fruit quality in kiwifruit (*Actinidia deliciosa* cv. Hayward). *Sci. Hortic.* **2001**, *91*, 189–199. [\[CrossRef\]](#)
9. Salinero, M.C.; Vela, P.; Sainz, M.J. Phenological growth stages of kiwifruit (*Actinidia deliciosa* ‘Hayward’). *Sci. Hortic.* **2009**, *121*, 27–31. [\[CrossRef\]](#)
10. Germer, S.; Dongen, R.V.; Kern, J. Decomposition of cherry tree prunings and their short-term impact on soil quality. *Appl. Soil Ecol.* **2017**, *117–118*, 156–164. [\[CrossRef\]](#)
11. Sofo, A.; Mininni, A.N.; Ricciuti, P. Comparing the effects of soil fauna on litter decomposition and organic matter turnover in sustainably and conventionally managed olive orchards. *Geoderma* **2020**, *372*, 114393. [\[CrossRef\]](#)
12. Webber, S.M.; Bailey, A.P.; Huxley, T.; Potts, S.G.; Lukac, M. Traditional and cover crop-derived mulches enhance soil ecosystem services in apple orchards. *Appl. Soil Ecol.* **2022**, *178*, 104569.
13. Liu, S.; Yang, R.; Peng, X.; Hou, C.; Ma, J.; Guo, J. Contributions of plant litter decomposition to soil nutrients in ecological tea gardens. *Agriculture* **2022**, *12*, 957. [\[CrossRef\]](#)
14. Notaro, K.d.A.; Medeiros, E.V.d.; Duda, G.P.; Silva, A.O.; Moura, P.M.d. Agroforestry systems, nutrients in litter and microbial activity in soils cultivated with coffee at high altitude. *Sci. Agric.* **2014**, *71*, 87–95. [\[CrossRef\]](#)
15. Aldana, J.P.; Rahman, M.; Conrado, P.; Cruz, A.I.; Arenas, O.R. Litter Decomposition Process in Coffee Agroforestry Systems. *J. For. Environ. Sci.* **2019**, *35*, 121–139. [\[CrossRef\]](#)
16. Mathew, S.; Kumar, R.R.; Marichamy, M.; Kumar, P.M. Carbon sequestration in tea soil through burial of pruning and its impact on biomass production and soil characteristics. *J. Plant. Crops* **2012**, *40*, 125–131.
17. Bhatnagar, J.M.; Peay, K.G.; Treseder, K.K. Litter chemistry influences decomposition through activity of specific microbial functional guilds. *Ecol. Monogr.* **2018**, *88*, 429–444. [\[CrossRef\]](#)
18. Ågren, G.; Hyvönen, R.; Berglund, S.; Hobbie, S. Estimating the critical N: C from litter decomposition data and its relation to soil organic matter stoichiometry. *Soil Biol. Biochem.* **2013**, *67*, 312–318. [\[CrossRef\]](#)
19. Talbot, J.M.; Treseder, K.K. Interactions among lignin, cellulose, and nitrogen drive litter chemistry–decay relationships. *Ecology* **2012**, *93*, 345–354. [\[CrossRef\]](#)
20. Krishna, M.P.; Mohan, M. Litter decomposition in forest ecosystems: A review. *Energy Ecol. Environ.* **2017**, *2*, 236–249. [\[CrossRef\]](#)
21. Spohn, M.; Berg, B. Import and release of nutrients during the first five years of plant litter decomposition. *Soil Biol. Biochem.* **2023**, *176*, 108878. [\[CrossRef\]](#)
22. Tian, L.; Shi, W. Short-term effects of plant litter on the dynamics, amount, and stoichiometry of soil enzyme activity in agroecosystems. *Eur. J. Soil Biol.* **2014**, *65*, 23–29. [\[CrossRef\]](#)
23. Mooshammer, M.; Wanek, W.; Zechmeister-Boltenstern, S.; Richter, A. Stoichiometric imbalances between terrestrial decomposer communities and their resources: Mechanisms and implications of microbial adaptations to their resources. *Front. Microbiol.* **2014**, *5*, 22. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Wickings, K.; Grandy, A.S.; Reed, S.C.; Cleveland, C.C. The origin of litter chemical complexity during decomposition. *Ecol. Lett.* **2012**, *15*, 1180–1188. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Trinsoutrot, I.; Recous, S.; Bentz, B.; Linères, M.; Nicolardot, B. Biochemical quality of crop residues and carbon and nitrogen mineralization kinetics under nonlimiting nitrogen conditions. *Soil Sci. Soc. Am. J.* **2000**, *64*, 918–926. [\[CrossRef\]](#)
26. Lu, Y.; Gao, Z.; Mao, J.; Chen, L.; Zhang, X.; Wang, X. Litter Decomposition Characteristics and Variety Differences in a Kiwifruit Orchard in Subtropical Climate Zone of China. *Agronomy* **2023**, *13*, 774. [\[CrossRef\]](#)
27. Levine, K.E.; Ross, G.T.; Fernando, R.A.; Blake, J.C.; Sparacino, C.M.; Pellizzari, E.D. Trace Element Content of Senna Study Material and Selected Senna-Based Dietary Supplements as Determined by Inductively Coupled Plasma-Optical Emission Spectrometry and Inductively Coupled Plasma-Mass Spectrometry. *Commun. Soil Sci. Plant Anal.* **2004**, *35*, 835–851. [\[CrossRef\]](#)
28. Chevallier, E.; Chekri, R.; Zinck, J.; Guérin, T.; Noël, L. Simultaneous determination of 31 elements in foodstuffs by ICP-MS after closed-vessel microwave digestion: Method validation based on the accuracy profile. *J. Food Compos. Anal.* **2015**, *41*, 35–41. [\[CrossRef\]](#)
29. Zhao, Q.; Bai, J.; Liu, P.; Gao, H.; Wang, J. Decomposition and Carbon and Nitrogen Dynamics of *Phragmites australis* Litter as Affected by Flooding Periods in Coastal Wetlands. *CLEAN—Soil Air Water* **2015**, *43*, 441–445. [\[CrossRef\]](#)
30. Chen, Y.; Wang, L.; Yang, Y.; Guo, Y.; Han, M.; Wang, J.; Shao, L. Resource assessment of fruit tree pruning branches and fertilizer utilization potential analysis in Shandong Province. *China Fruits* **2020**, *44*, 92–95. [\[CrossRef\]](#)
31. Zhang, M.; Cheng, X.; Geng, Q.; Shi, Z.; Luo, Y.; Xu, X. Leaf litter traits predominantly control litter decomposition in streams worldwide. *Glob. Ecol. Biogeogr.* **2019**, *28*, 1469–1486. [\[CrossRef\]](#)
32. Hättenschwiler, S.; Jørgensen, H.B. Carbon quality rather than stoichiometry controls litter decomposition in a tropical rain forest. *J. Ecol.* **2010**, *98*, 754–763. [\[CrossRef\]](#)
33. Jabiol, J.; Cornut, J.; Tlili, A.; Gessner, M.O. Interactive effects of dissolved nitrogen, phosphorus and litter chemistry on stream fungal decomposers. *FEMS Microbiol. Ecol.* **2018**, *94*, fty151. [\[CrossRef\]](#)

34. Schneider, T.; Keiblinger, K.M.; Schmid, E.; Sterflinger-Gleixner, K.; Ellersdorfer, G.; Roschitzki, B.; Richter, A.; Eberl, L.; Zechmeister-Boltenstern, S.; Riedel, K. Who is who in litter decomposition? Metaproteomics reveals major microbial players and their biogeochemical functions. *ISME J.* **2012**, *6*, 1749–1762. [[CrossRef](#)] [[PubMed](#)]
35. Berg, B.; McClaugherty, C. Decomposition as a Process—Some Main Features. In *Plant Litter: Decomposition, Humus Formation, Carbon Sequestration*; Berg, B., McClaugherty, C., Eds.; Springer International Publishing: Cham, Switzerland, 2020; pp. 13–43.
36. Purahong, W.; Kapturska, D.; Pecyna, M.J.; Schulz, E.; Schloter, M.; Buscot, F.; Hofrichter, M.; Krüger, D. Influence of different forest system management practices on leaf litter decomposition rates, nutrient dynamics and the activity of ligninolytic enzymes: A case study from Central European forests. *PLoS ONE* **2014**, *9*, e93700.
37. Purahong, W.; Wubet, T.; Lentendu, G.; Schloter, M.; Pecyna, M.J.; Kapturska, D.; Hofrichter, M.; Krüger, D.; Buscot, F. Life in leaf litter: Novel insights into community dynamics of bacteria and fungi during litter decomposition. *Mol. Ecol.* **2016**, *25*, 4059–4074. [[PubMed](#)]
38. Keiluweit, M.; Nico, P.; Harmon, M.E.; Mao, J.; Pett-Ridge, J.; Kleber, M. Long-term litter decomposition controlled by manganese redox cycling. *Proc. Natl. Acad. Sci. USA* **2015**, *112*, E5253–E5260. [[CrossRef](#)]
39. Li, Q.; Zhang, M.; Geng, Q.; Jin, C.; Zhu, J.; Ruan, H.; Xu, X. The roles of initial litter traits in regulating litter decomposition: A “common plot” experiment in a subtropical evergreen broadleaf forest. *Plant Soil* **2020**, *452*, 207–216. [[CrossRef](#)]
40. Zhang, T.; Luo, Y.; Chen, H.Y.H.; Ruan, H. Responses of litter decomposition and nutrient release to N addition: A meta-analysis of terrestrial ecosystems. *Appl. Soil Ecol.* **2018**, *128*, 35–42. [[CrossRef](#)]
41. Yue, K.; Yang, W.; Peng, Y.; Zhang, C.; Huang, C.; Xu, Z.; Tan, B.; Wu, F. Dynamics of multiple metallic elements during foliar litter decomposition in an alpine forest river. *Ann. For. Sci.* **2016**, *73*, 547–557. [[CrossRef](#)]
42. Leroy, C.J.; Marks, J.C. Litter quality, stream characteristics and litter diversity influence decomposition rates and macroinvertebrates. *Freshw. Biol.* **2006**, *51*, 605–617. [[CrossRef](#)]
43. Lovett, G.M.; Arthur, M.A.; Crowley, K.F. Effects of calcium on the rate and extent of litter decomposition in a northern hardwood forest. *Ecosystems* **2016**, *19*, 87–97. [[CrossRef](#)]
44. García-Palacios, P.; McKie, B.G.; Handa, I.T.; Frainer, A.; Hättenschwiler, S. The importance of litter traits and decomposers for litter decomposition: A comparison of aquatic and terrestrial ecosystems within and across biomes. *Funct. Ecol.* **2016**, *30*, 819–829. [[CrossRef](#)]
45. Yue, K.; Ni, X.; Fornara, D.A.; Peng, Y.; Liao, S.; Tan, S.; Wang, D.; Wu, F.; Yang, Y. Dynamics of calcium, magnesium, and manganese during litter decomposition in alpine forest aquatic and terrestrial ecosystems. *Ecosystems* **2021**, *24*, 516–529. [[CrossRef](#)]
46. Gautam, M.K.; Lee, K.-S.; Berg, B.; Song, B.-Y.; Yeon, J.-Y. Trends of major, minor and rare earth elements in decomposing litter in a cool temperate ecosystem, South Korea. *Chemosphere* **2019**, *222*, 214–226. [[CrossRef](#)]
47. Sun, T.; Cui, Y.; Berg, B.; Zhang, Q.; Dong, L.; Wu, Z.; Zhang, L. A test of manganese effects on decomposition in forest and cropland sites. *Soil Biol. Biochem.* **2019**, *129*, 178–183. [[CrossRef](#)]
48. Berg, B.; Kjønaas, O.; Johansson, M.-B.; Erhagen, B.; Åkerblom, S. Late stage pine litter decomposition: Relationship to litter N, Mn, and acid unhydrolyzable residue (AUR) concentrations and climatic factors. *For. Ecol. Manag.* **2015**, *358*, 41–47. [[CrossRef](#)]
49. Innangi, M.; Schenk, M.K.; d’Alessandro, F.; Pinto, S.; Menta, C.; Papa, S.; Fioretto, A. Field and microcosms decomposition dynamics of European beech leaf litter: Influence of climate, plant material and soil with focus on N and Mn. *Appl. Soil Ecol.* **2015**, *93*, 88–97. [[CrossRef](#)]
50. Song, Q.-N.; Ouyang, M.; Yang, Q.-P.; Lu, H.; Yang, G.-Y.; Chen, F.-S.; Shi, J.-M. Degradation of litter quality and decline of soil nitrogen mineralization after moso bamboo (*Phyllostachys pubescens*) expansion to neighboring broadleaved forest in subtropical China. *Plant Soil* **2016**, *404*, 113–124.
51. Martínez-García, L.; Korthals, G.; Brussaard, L.; Mainardi, G.; De Deyn, G. Litter quality drives nitrogen release, and agricultural management (organic vs. conventional) drives carbon loss during litter decomposition in agro-ecosystems. *Soil Biol. Biochem.* **2021**, *153*, 108115.
52. Hess, L.J.; Hinckley, E.-L.S.; Robertson, G.P.; Matson, P.A. Rainfall intensification increases nitrate leaching from tilled but not no-till cropping systems in the US Midwest. *Agric. Ecosyst. Environ.* **2020**, *290*, 106747. [[CrossRef](#)]
53. Schuster, M.J. Increased rainfall variability and N addition accelerate litter decomposition in a restored prairie. *Oecologia* **2016**, *180*, 645–655. [[CrossRef](#)] [[PubMed](#)]
54. Meyer, U.-N.; Tischer, A.; Freitag, M.; Klaus, V.H.; Kleinebecker, T.; Oelmann, Y.; Kandeler, E.; Hölzel, N.; Hamer, U. Enzyme kinetics inform about mechanistic changes in tea litter decomposition across gradients in land-use intensity in Central German grasslands. *Sci. Total Environ.* **2022**, *836*, 155748. [[CrossRef](#)]
55. Ge, X.; Xiao, W.; Zeng, L.; Huang, Z.; Zhou, B.; Schaub, M.; Li, M.-H. Relationships between soil–litter interface enzyme activities and decomposition in *Pinus massoniana* plantations in China. *J. Soils Sediments* **2017**, *17*, 996–1008. [[CrossRef](#)]
56. Kotrocó, Z.; Veres, Z.; Fekete, I.; Krakomperger, Z.; Tóth, J.A.; Lajtha, K.; Tóthmérész, B. Soil enzyme activity in response to long-term organic matter manipulation. *Soil Biol. Biochem.* **2014**, *70*, 237–243. [[CrossRef](#)]
57. Lin, S.; Liu, Z.; Wang, Y.; Li, J.; Wang, G.; Ye, J.; Wang, H.; He, H. Soil metagenomic analysis on changes of functional genes and microorganisms involved in nitrogen-cycle processes of acidified tea soils. *Front. Plant Sci.* **2022**, *13*, 998178. [[CrossRef](#)]
58. Hu, Y.; Wang, S.; Zeng, D. Effects of single Chinese fir and mixed leaf litters on soil chemical, microbial properties and soil enzyme activities. *Plant Soil* **2006**, *282*, 379–386. [[CrossRef](#)]

59. Wu, P.-P.; Jiang, L.-X.; Zhang, Y.; Tu, Q.-H.; Mao, R. Manganese addition accelerates litter decomposition and alters litter mixing effects in the late stage in subtropical plantations of southern China. *Plant Soil* **2022**, *481*, 501–510. [[CrossRef](#)]
60. Zhang, H.; Cao, Y.; Lyu, J. Decomposition of different crop straws and variation in straw-associated microbial communities in a peach orchard, China. *J. Arid. Land* **2021**, *13*, 152–164. [[CrossRef](#)]
61. Zhang, Z.; Ge, S.; Fan, L.-C.; Guo, S.; Hu, Q.; Ahammed, G.J.; Yan, P.; Zhang, L.-P.; Li, Z.-Z.; Zhang, J.-Y. Diversity in rhizospheric microbial communities in tea varieties at different locations and tapping potential beneficial microorganisms. *Front. Microbiol.* **2022**, *13*, 1027444.

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