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Litter Decomposition Characteristics and Variety Differences in a Kiwifruit Orchard in Subtropical Climate Zone of China

Yupeng Lu [1], Zhu Gao [1,2], Jipeng Mao [1], Lu Chen [2], Xiaoli Zhang [2] and Xiaoling Wang [1,*]

[1] Institute of Biological Resources, Jiangxi Academy of Sciences, Nanchang 330096, China
[2] Jinggangshan Institute of Biotechnology, Ji'an 343016, China
* Correspondence: wangxiaoling@jxas.ac.cn

Abstract: The aim of this study was to reveal the decomposition dynamics of kiwifruit litter and verify the variety differences and provide a scientific basis for rational fertilization in orchard. Kiwifruit litters of two varieties ('Hongyang' and 'Jinyan') were taken as the objects; the litter decomposition rate, the dynamics of macro-elements and micro-elements, and soil enzyme activities during the decomposition process were analyzed. The results showed that the litter decomposition rate of 'Hongyang' kiwifruit was faster than that of 'Jinyan' kiwifruit, because of the higher initial N and P content in the litter of the 'Hongyang' kiwifruit. The dynamic trends of macro-elements and micro-elements during litter decomposition of two varieties were similar. The C content was relatively stable, the P content was fluctuant, and the K content was decreasing. The contents of N, Fe, Mn, Cu, and Zn were increasing. The contents of Ca, Mg, and B increased first and then decreased. After 180 days of the decomposition experiment, more than 75% of the initial contents of C, N, P, K, Ca, Mg, and B were released. The dynamic trends of the soil enzyme activities of two varieties were generally similar. Due to the slow decomposition rate, the dynamic trends of soil enzyme activities of 'Jinyan' kiwifruit litter each showed hysteresis. The contents of Ca, Mg, and Mn were significantly correlated with some soil enzyme activities. In conclusion, the litter substrate quality of the two kiwifruit varieties is different, which leads to the difference in the decomposition rate. The litter decomposition of kiwifruit is an important supplement to the macro-element in orchard soil.

Keywords: decomposition rate; substrate quality; nutrient release; soil enzyme activities; orchard ecosystem

Citation: 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. https://doi.org/10.3390/agronomy13030774

Academic Editor: Andrea Baglieri

Received: 7 February 2023
Revised: 1 March 2023
Accepted: 3 March 2023
Published: 7 March 2023

1. Introduction

Litter decomposition is an essential part of nutrient cycling between the plant and environment [1–3]. Moreover, litter decomposition is an important ecological and economic issue in the orchard ecosystem. Fruit trees absorb nutrients form the surrounding environment and store a portion of the nutrients in the fruit, which eventually leaves the orchard ecosystem as an economic product. Therefore, there is a nutrient gap in the orchard ecosystem, which needs to be supplemented by exogenous nutrients [4]. Litter decomposition is a process in which plants release nutrients back to the soil, including macro-elements (such as N, P, and K) and micro-elements (such as Fe, Mn, and Zn), as a complement to synthetic fertilization [5,6]. Thus, the study of litter decomposition in the orchard ecosystem can guide precision fertilization, and reduce economic input and increase orchard benefits [7].

Compared with other ecosystems, such as forests and grassland, the litter of an orchard has many unique characteristics, due to human management activities [8]. The first is the source of litter. Except for natural litter, a portion of the litter in the orchard is pruned branches and leaves [9]. Without going through the stage of nutrient and water reflux in the natural fall process, the pruned branches and leaves tend to have higher nutrient and water contents. The N and lignin contents of litters are the most significant in

regulating the rates of decomposition [10]. In general, the decomposition rate of litter with a high N content, low lignin content, and low C/N ratio is faster. The different substrate quality in turn affects the decomposition rate of litters [11]. The second is the environment of litter decomposition. Many management activities will affect the soil properties and biotic communities. For example, fertilization and irrigation affect the contents of soil nutrients and water [12–14]. Interplanting some herbs, such as *Trifolium repens L.* and *Lolium perenne L.*, can improve soil structure and fertility and change the soil microbial community structure [15–17]. Spraying pesticides will inhibit the activities of soil fauna [18,19]. The different decomposition environment in turn affects the decomposition rate. Therefore, the study of litter decomposition in the orchard ecosystem can analyze the decomposition characteristics of litter from different angles and improve the research system.

In the study of litter decomposition, current studies mainly focus on the decomposition process, the factors affecting the decomposition, and the impact of decomposition on the environment (such as soil, atmosphere, and water). Specifically to the orchard ecosystems, the three research contents mainly include: (1) the decomposition process: mass loss, nutrient release, activities of decomposer and soil enzyme [20,21]; (2) affecting factors: the source and time of litter production [20]; and (3) impact of decomposition: improvement of soil fertility [22,23]. For the nutrient dynamics during decomposition, macro-elements (such as N and P) are research hotspots, while micro-elements are paid less attention. Micro-elements are indispensable nutrients for plant growth. For example, iron deficiency leads to the yellowing of young leaves and veins [24], and zinc deficiency leads to the shortening of internodes [25]. In addition, micro-elements play an important role in litter decomposition; for example, Mn is an essential component in the synthesis of lignin-degrading enzymes [26]. For the source of litter production, variety difference is a neglected problem in the study of litter decomposition in orchard ecosystems. Due to artificial breeding, there are often many varieties of a fruit, and there may be differences in the phenology, leaf, and fruit traits among varieties, which in turn lead to differences in the substrate quality of the litter.

Kiwifruit (*Actinidia chinensis Planch.*) is a very popular fruit, and China is its main planting area [27]. Based on the data provided by the Food and Agriculture Organization of the United Nations (FAO), as of 2020, the harvested area of the kiwifruit of China is 184,554 ha, accounting for 68.2% of the world's total harvested area, and the yield is 2.23 million tons, accounting for 50.6% of the world's total yield. In order to increase the yield of kiwifruit, fruit famers will prune branches and leaves in winter and cover them on the soil surface, and that forms the litter layer of kiwifruit. Kiwifruit orchard production requires a lot of nutrients. The research showed that 540 g of N, 82 g of P, and 418 g of K are consumed for every 100 kg of fruit produced in a ten-year-old kiwifruit orchard in Shaanxi Province, China [28]. After conversion according to the orchard output (40.16 t/ha), 217 kg of N, 33 kg of P, and 168 kg of K are required per hectare. Therefore, the nutrients released by litter decomposition are important supplements to the kiwifruit orchard ecosystem. At present, studies on litter decomposition in orchard ecosystems has been carried out in some orchards, such as apple, cherry, and peach orchards [7,9,29]. However, the litter decomposition of kiwifruit orchards has not been reported. On the other hand, there are many varieties of kiwifruit, and one orchard often grows more than one variety. There may be differences in the litter substrate quality among varieties, which in turn lead to differences in the decomposition process. Therefore, this study took kiwifruit litter of two varieties ('Hongyang' and 'Jinyan') as the objects to solve two scientific problems by: (1) revealing the decomposition dynamic of kiwifruit litter and (2) verifying the variety differences. We analyzed the decomposition rate, nutrient dynamics (including macro-elements and micro-elements) and soil enzyme activities during litter decomposition. Furthermore, the variety differences in litter decomposition and the correlation between litter nutrients and soil enzyme activities were analyzed. Orchardists could adjust fertilization measures according to the decomposition process and nutrient

release of fruit tree litter. This study could provide a reference for scientific fertilization in kiwifruit orchards and reveal the dynamic of litter decomposition in orchard ecosystems.

2. Materials and Methods

2.1. Study Site

The study site was located in Fengxin County, Jiangxi Province, Southeast China (28°40′36″ N, 115°19′02″ E). This region is a subtropical humid climate with warm temperatures and abundant rainfall. The mean annual temperature is 17.6 °C, and the mean annual precipitation is 1671.5 mm yr^{-1}. The mean annual relative humidity is 79%, the annual frost-free period is about 260 d, and the annual sunshine duration is 1784.9 h. This region is rich in wild kiwifruit resources and has nearly 50 years of kiwifruit cultivation history, making it known as the 'Hometown of *A. chinensis*'. At present, the total cultivated area of kiwifruit is 5300 ha, and the total output is 55,000 tons.

2.2. Study Plant Species

The study plant species were 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, and they were the two main cultivated varieties in Fengxin County. 'Hongyang' kiwifruit is a diploid of *A. chinensis*, and it is bred from the seedlings of *A. chinensis* after budding [27]. The leaves are heart-shaped. The fruit is cylindrical or obovate in shape, with the green pericarp and bright red pulp around the seeds. The flowering period is April, the fruiting period is August to September, and the deciduous period is November to December.

The 'Jinyan' kiwifruit is a tetraploid of *A. chinensis*, and it is bred by crossbreeding with *Actinidia eriantha Benth.* as the female parent and *A. chinensis* as the male parent [30]. The leaves are leathery and suborbicular or oblate in shape. The fruit is prolate cylindrical in shape, with the brown pericarp and golden pulp. The flowering period is May, the fruiting period is September to October, and the deciduous period is November to December. For the substrate quality, the litter of the 'Hongyang' kiwifruit had higher N and P contents, higher C/N, higher C/P, and lower N/P. Thus, the substrate quality of the 'Hongyang' kiwifruit litter was better (Table 1). In addition, the litter of the 'Hongyang' kiwifruit had higher Mg and Mn contents. The litter of 'Jinyan' had higher K, Ca, Fe, and Zn contents.

Table 1. Initial nutrients content of air-dried litters of 'Hongyang' kiwifruit and 'Jinyan' kiwifruit.

Nutrients	Hongyang	Jinyan	Nutrients	Hongyang	Jinyan
C (g/kg)	401.0 ± 8.5	402.3 ± 9.6	Ca (g/kg)	7.6 ± 0.4	14.7 ± 1.6 *
N (g/kg)	24.9 ± 1.2 *	18.9 ± 0.8	Mg(g/kg)	3.3 ± 0.1 *	1.3 ± 0.1
P (g/kg)	4.0 ± 0.6	3.5 ± 0.3	Fe (mg/kg)	144.0 ± 6.8	19.0 ± 1.8 *
K (g/kg)	12.1 ± 0.5	21.6 ± 1.2 *	Mn (mg/kg)	456.0 ± 9.3 **	216.0 ± 6.7
C/N	16.1 ± 1.1	21.3 ± 1.4 *	Cu (mg/kg)	6.3 ± 0.4	6.0 ± 0.9
C/P	100.3 ± 15.6	114.9 ± 13.2	Zn (mg/kg)	12.0 ± 1.3	23.1 ± 2.3 *
N/P	6.2 ± 1.1	5.4 ± 0.7	B (mg/kg)	34.6 ± 0.7	31.7 ± 1.6

Notes: mean ± standard deviation; *: $p < 0.05$; **: $p < 0.01$.

2.3. Litter Decomposition Study

The field study was performed in a 10-year-old kiwifruit orchard with an area of 15 ha. The kiwifruit trees were planted in a 2 m × 4 m spacing, and the average number of trees per hectare was 825. The annual fertilization amount of each hectare orchard was 4.5 t of organic fertilizer, 150 kg of urea, 300 kg of $Ca(H_2PO_4)_2$, and 150 kg of K_2SO_4. The fertilization time was the germination period (from February to March), fruit expanding period (from May to June), and postharvest period (from November to December), and each fertilizer amount accounted for 20%, 30%, and 50% of the annual fertilizer amount, respectively. The soil water content of the orchard should be kept at 65%–80% of the field water capacity, and irrigation would be carried out when it was lower than 60%. The soil type of the orchard was red soil, and the physicochemical characterization of the soil was determined before the litter decomposition experiment. The results showed that there was

no significant difference in soil properties between the orchards of the 'Hongyang' and 'Jinyan' kiwifruit (Table S1).

The litter bag method was used in this litter decomposition study. Five quadrats of 5 × 5 m were randomly set in the planting areas of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, respectively. The leaf litter was collected in each quadrat after orchard pruning in December 2020, and then the litter was dried for 48 h at 60 °C for preservation. A total of 10.0 g of litter was placed into 15 cm × 25 cm nylon mesh bags with a 0.5 mm mesh diameter. In each quadrat, six bags were placed on the soil surface and secured with plastic nails (the nails were collected at the end of the experiment). There were 30 litter bags for the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, respectively. In addition, a part of the litter was preserved for the determination of initial nutrient content, and 100 g surface soil was sampled in each quadrat for the determination of the initial soil enzyme activities. During the litter decomposition study, a decomposition bag was taken every 30 days, and a 100 g surface soil (0–10 cm) sample under the decomposition bag was taken at the same time. This study was carried out for 180 days with a total of six samples (2 January to 30 June 2021). The meteorological conditions of the study area during the experiment are shown in Figure 1. The data of temperature and precipitation were obtained from a small weather station in the orchard, and the measured height of the temperature was 1.5 m above the ground.

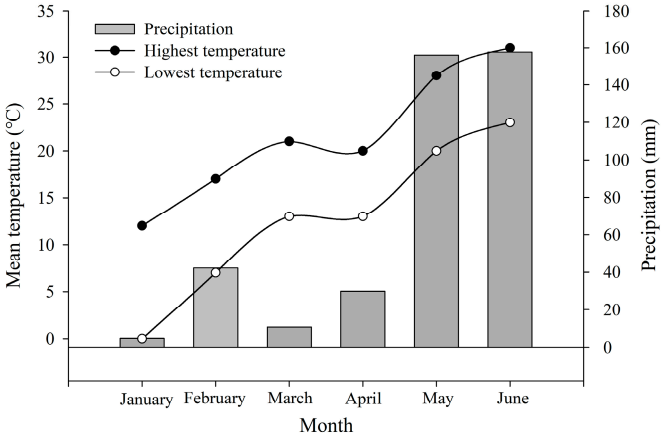

Figure 1. The meteorological conditions of the study area during the experiment.

2.4. Litter Residue Analysis

The litter decomposition residue in the decomposition bag was taken out and placed in a 0.15 mm soil sieve to wash off the surface sundries with water, and then the residue was dried for 48 h at 60 °C. After weighing, the residue was ground into powder for the determination of the nutrient contents. The total carbon (C) and total nitrogen (N) contents were determined using the element analyzer (vario MACRO cube, Elementar, Hanau, Hessian, Germany) [31].

The total phosphorus (P) content was determined using the colorimetric method. After the plant sample was digested with H_2SO_4, took 10 mL of the digested solution and put it into a 50 mL volumetric flask. Added 2 drops of dinitrophenol indicator, and then added 6 mol/L NaOH to neutralize the solution until its color turned yellow. Added 10 mL of ammonium vanadate molybdate and fixed the volume with distilled water. After 15 min, the colorimetry was carried out at the 440 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). At the same time, took 10 mL of the digested solution and put it into a 50 mL volumetric flask. Used distilled water to volume to the scale. The total potassium (K) content could be obtained via determination with the atomic absorption spectrometer (Analyst 800, PERKINELMER, Waltham, MA, USA).

According to the methods in Cakmak et al. [32] and Masson et al. [33], the plant sample was digested using a closed microwave with mixed acid of HNO_3–H_2O_2. The contents

of the calcium (Ca), magnesium (Mg), iron (Fe), and manganese (Mn) were determined using the inductively coupled plasma optical emission spectrometer (ICP-OES) (ICPE-9800, Shimadzu, Kyoto, Japan). The contents of the copper (Cu), zinc (Zn), and boron (B) were determined using the inductively coupled plasma mass spectrometry (ICP-MS) (ICPMS2030, Shimadzu, Kyoto, Japan).

2.5. Analysis of Soil Enzyme Activity

In order to analyze the role of soil enzymes in this litter decomposition study, we determined the activities of five soil enzymes according to the methods in Zhang et al. [34]. Sucrase promotes the hydrolysis of sucrose to glucose and fructose and is one of the important soil enzymes that degrade carbon compounds in litters. The activity of sucrase was determined using the colorimetric method. Weighed 5 g of air-dried soil and put it into a 50 mL triangular flask. Added 15 mL of 8% sucrose solution, 5 ml pH of 5.5 phosphate buffer, and 5 drops of toluene. Incubated at 37 °C for 24 h and then filtered. Took 1 ml of filtrate, injected it into a 50 mL volumetric flask, added 3 ml of 3,5-dinitrosalicylic acid, and bathed in boiling water for 5 min. After cooling, used distilled water to volume to the scale, and the colorimetry was carried out at the 508 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan).

β-1,4-glucosidase is an enzyme involved in the carbon biological cycle that promotes the decomposition of polysaccharides and β-glucoside into glucose. The activity of β-1,4-glucosidase was determined via nitrophenol colorimetry. Weighed 1 g of air-dried soil and put it into a 50 mL triangular flask. Added 0.2 mL toluene, 1.8 mL distilled water, 3 mL pH of 4.8 phosphoric acid–citrate acid buffer, and 1.2 mL of 0.05 mol/L p-nitrobenzene-β-D-glucoside. Incubated at 30 °C for 1 h. After incubation at 30 °C for 1 h, added 16 mL ethanol and filtered. Took 4 mL of filtrate, injected it into a 50 mL volumetric flask, added 4 mL of trismetyl aminomethane, and then used distilled water to volume to the scale. The colorimetry was carried out at the 400 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan).

Polyphenol oxidase participates in the transformation of aromatic compounds in soil, oxidizes phenols into quinones, and is a medium of soil humification. The activity of polyphenol oxidase was determined using the colorimetric method. Weighed 1 g of air-dried soil and put it into a 50 mL triangular flask. Added 10 mL of 1% pyrogallic acid. Incubated at 30 °C for 2 h. Added 4 mL of pH 4.5 phosphoric acid–citrate acid buffer and 35 mL diethyl ether. After extraction for 30 min, the colorimetry was carried out at the 430 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan).

Protease participates in the transformation of amino acids, proteins, and other organic compounds containing protein nitrogen in soil. The activity of protease was determined using the colorimetric method. Weighed 4 g of air-dried soil and put it into a 50 mL triangular flask. Added 20 mL of 1% casein and 1 mL of toluene. Incubated at 30 °C for 24 h. Added 2 mL of 0.05 mol/L H_2SO_4 and 12 mL of 20% Na_2SO_4. Centrifuged the mixture for 15 min, took 2 mL of supernatant and put it into a 50 mL volumetric flask. Added 1 mL ninhydrin, and bathed in boiling water for 10 min. After cooling, used distilled water to volume to the scale, and the colorimetry was carried out at the 500 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan).

Phosphatase participates in the transformation of organophosphorus in soil, which can accelerate the dephosphorization of organophosphorus. The activity of phosphatase was determined using the colorimetric method of disodium phenyl phosphate. Weighed 5 g of air-dried soil and put it into a 50 mL triangular flask. Added 5 drops of toluene and 20 mL of 0.5% disodium phenyl phosphate. Incubated at 37 °C for 2 h and then filtered. Took 5 mL of filtrated and injected it into a 50 mL volumetric flask. Added 20 mL distilled water, 0.25 mL of pH 9.8 NH_4Cl–NH_4OH buffer, 0.5 mL ampyrone, and 0.5 mL potassium ferricyanide. Used distilled water to volume to the scale, and the colorimetry was carried out at the 510 nm wavelength of the spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). The reagents used in this study were provided by Xilong Scientific Co., Ltd., (Shantou, Guangdong, China).

2.6. Data Analysis

The exponential decay model was used to fit the litter residue (converted to residual rate) and calculated the litter decomposition rate using the SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA, USA). The equation of model is as follows [34]:

$$R = ae^{-bt} + ce^{-dt}$$

where R is the residual rate of litter, a, b, c, and d are the model parameter, t is the decomposition time of litter. Based on this model, the half-life period ($T_{0.5}$, the time of litter to decompose by 50%) and turnover period ($T_{0.05}$, the time of litter to decompose by 95%) of litter decomposition were calculated.

In addition, the proportion of nutrient release was calculated to reveal the nutrient release from the litter decomposition. The calculation formula is as follows:

$$P = \frac{W_0 \times C_0 - W_1 \times C_1}{W_0 \times C_0} \times 100\%$$

where P is the proportion of nutrient release, W_1 and W_0 are the final and initial dry matter mass of litter, respectively. C_1 and C_0 are the final and initial nutrient concentrations of litter, respectively.

Moreover, one-way ANOVA was used to compare the difference in the nutrient content of the litter between the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, and the least significant difference method (LSD, $p < 0.05$) was used for multiple comparison using the SPSS 26 software (IBM, Armonk, NYS, USA). Furthermore, we analyzed the correlation (Pearson correlation coefficient, r) between the nutrient content and soil enzyme activities during litter decomposition using the SPSS 26 software. The indexes with significant correlation were modeled and fitted using the SigmaPlot 12.5 software (Systat Software Inc., San Jose, CA, USA), and the relationship between them was analyzed.

3. Results

3.1. Litter Decomposition Rate

According to the model fitting results, the litter decomposition rate of the 'Hongyang' kiwifruit was faster (Figure 2). For the 'Hongyang' kiwifruit, the half-life period of litter decomposition was 38.5 days, and the turnover period was 271.0 days. For the 'Jinyan' kiwifruit, the half-life period of litter decomposition was 69.2 days, and the turnover period was 292.8 days.

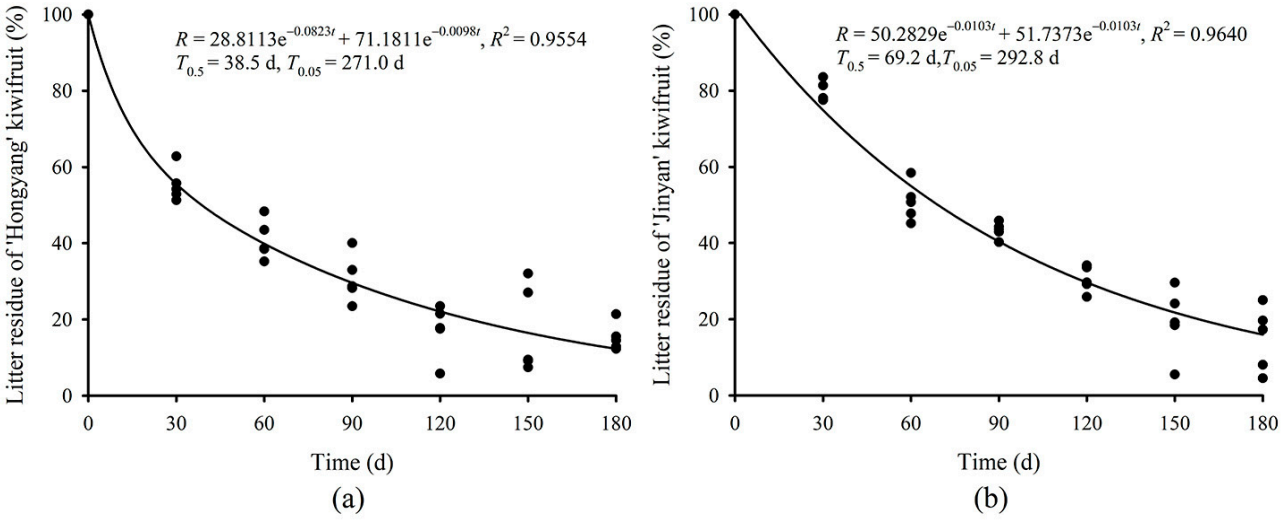

Figure 2. Model of litter decomposition and variety differences in the kiwifruit orchard. (**a**): Model of litter decomposition of 'Hongyang' kiwifruit; (**b**): model of litter decomposition of 'Jinyan' kiwifruit.

3.2. Dynamics of Nutrients during Litter Decomposition

Based on the nutrient contents during the litter decomposition of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, we plotted the nutrient content dynamic curves (Figures 3 and 4). The C content of the 'Hongyang' kiwifruit litter was relatively stable at 400 g/kg in the first 90 days of the decomposition experiment, and then gradually decreased to 340 g/kg. The C content of the 'Jinyan' kiwifruit litter was relatively stable at 400 mg/kg during the whole decomposition experiment. The N content of the 'Hongyang' kiwifruit litter increased in the first 30 days, and then remained stable between 30 g/kg to 32 g/kg. The N content of the 'Jinyan' kiwifruit litter increased in the first 120 days, and then remained stable between 26 g/kg to 28 g/kg. The P content of the two litters was in a fluctuating state of increase and decrease. The K content of the two litters decreased sharply in the first 60 days, and then remained stable at 1 g/kg. The dynamic trends in the Ca and Mg contents of the two litters increased first and then decreased. Moreover, the Ca content of the 'Jinyan' kiwifruit litter was higher during the decomposition experiment, and the Mg content of the 'Hongyang' kiwifruit litter was higher.

For the contents of Fe, Mn, Cu, and Zn, the dynamic trends were all gradually increasing. Furthermore, the contents of the Fe, Mn, Cu, and Zn of 'Hongyang' kiwifruit litters were higher during the decomposition experiment. The dynamic trends in the B content increased first and then decreased. Furthermore, the content of B in the 'Jinyan' kiwifruit litter was higher.

For the litter of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, the release proportion of macro-elements was relatively close, and all of them were more than 75% (Figure 5). Moreover, the litter of the 'Hongyang' kiwifruit released greater proportions of C, N, Ca, and Mg. For micro-elements, the release proportion varied greatly between the litter of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit. Specifically, the litter of the 'Hongyang' kiwifruit released greater proportions of Mn and B, and the litter of the 'Jinyan' kiwifruit released greater proportions of Cu and Zn. In addition, Fe was enriched by 21.09% during the litter decomposition of the 'Hongyang' kiwifruit, but was released by 72.81% for the 'Jinyan' kiwifruit. Furthermore, based on the initial content and release proportion of the nutrients, we calculated the release of 1 kg of litter and the release of 1 ha of orchard (Tables S2 and S3). For the 'Hongyang' kiwifruit, 1 kg of litter released 344.20 g of C, 19.80 g of N, 3.52 g of P, and 11.90 g of K after 180 days of decomposition experiments. Based on 7.5 t of litter production per hectare, the litter of 1 ha of orchard released 2581.53 kg of C, 148.51 kg of N, 26.39 kg of P, and 89.26 kg of K. For the 'Jinyan' kiwifruit, 1 kg of litter released 333.07 g of C, 14.33 g of N, 3.07 g of P, and 21.44 g of K. The litter of 1 ha of orchard released 2498.06 kg of C, 107.48 kg of N, 22.99 kgof P, and 160.83 kg of K.

3.3. Dynamics of Soil Enzyme Activities during Litter Decomposition

During litter decomposition of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit, the dynamic trends of the soil enzyme activities was similar. For sucrose of these two varieties, the activity increased gradually in the first 90 days of litter decomposition and then decreased gradually (Figure 6). For the β-1,4-glucosidase of the 'Hongyang' kiwifruit litter, the activity increased gradually in the first 90 days, then decreased gradually, and increased again after 150 days. For the β-1,4-glucosidase of the 'Jinyan' kiwifruit litter, the activity decreased in the first 30 days, then increased gradually, decreased again after 120 days, and increased again after 150 days. For polyphenol oxidase, the activity was low in the first 90 days and then gradually increased. For protease, the activity was high in the first 90 days and then gradually decreased. For phosphatase, the activity was high from 60 days to 180 days for thr 'Hongyang' kiwifruit litter, and the activity was high from 90 days to 180 days for the 'Jinyan' kiwifruit litter. In addition, from the value of the period of high enzyme activity, the activities of the sucrose, β-1,4-glucosidase, and phosphatase of the 'Hongyang' kiwifruit litter were higher. The activities of polyphenol oxidase and protease of the 'Jinyan' kiwifruit litter were higher.

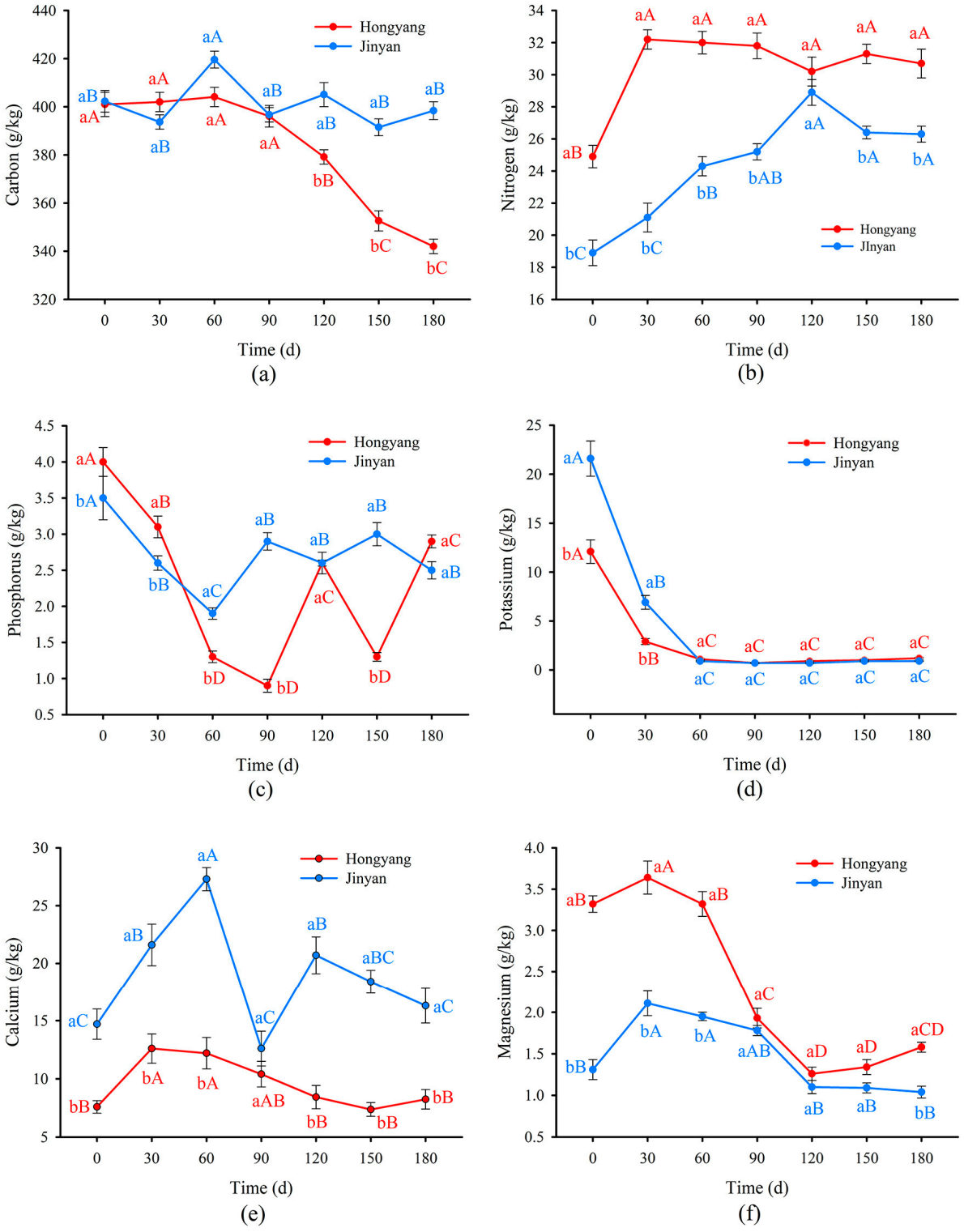

Figure 3. Macro-elements dynamic during litter decomposition and variety differences in the kiwifruit orchard. (**a**): The dynamic of C content; (**b**): the dynamic of N content; (**c**): the dynamic of P content; (**d**): the dynamic of K content; (**e**): the dynamic of Ca content; (**f**): the dynamic of Mg content. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in varieties ($p < 0.05$).

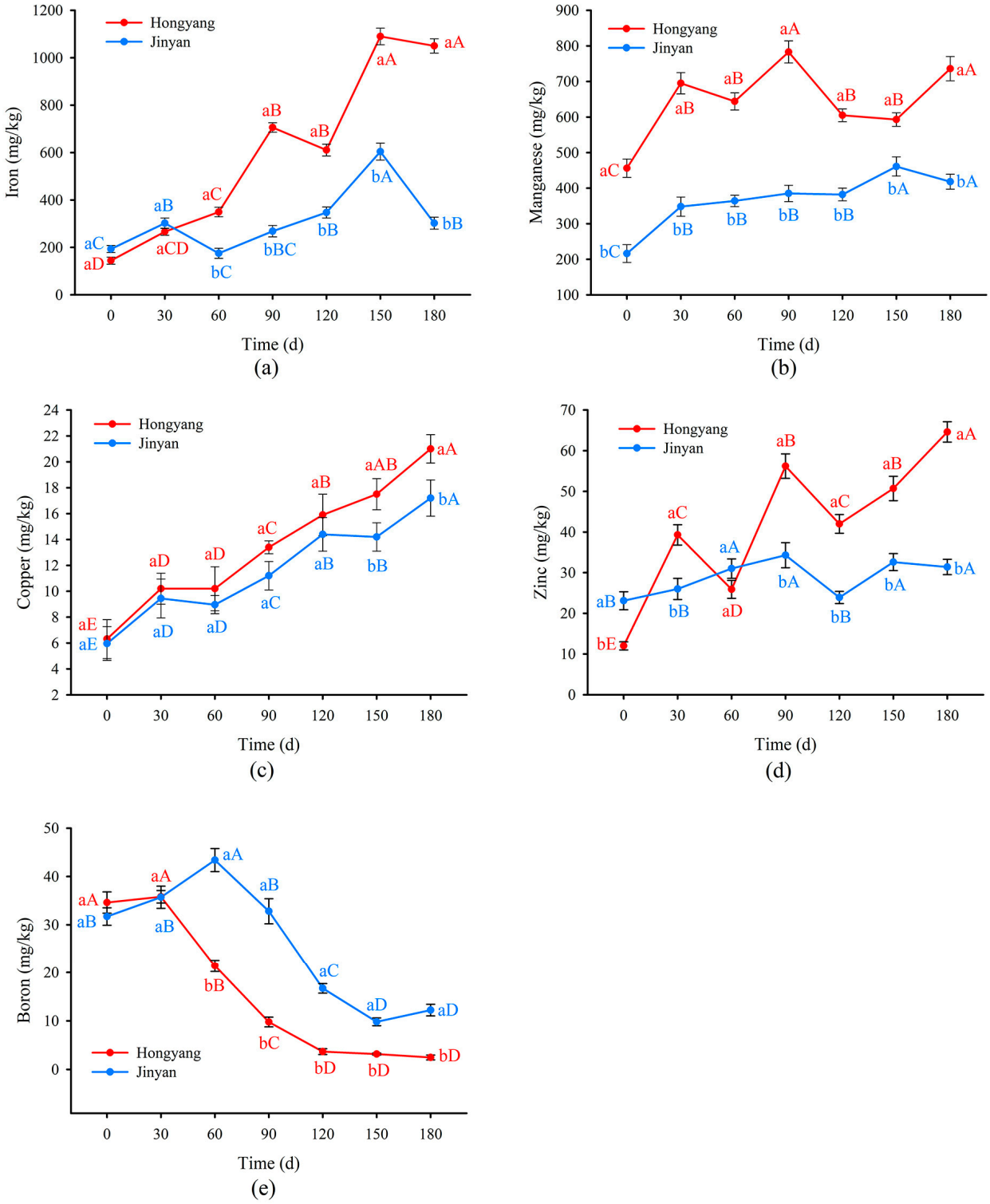

Figure 4. Micro-elements dynamic during litter decomposition and variety differences in the kiwifruit orchard. (**a**): The dynamic of Fe content; (**b**): the dynamic of Mn content; (**c**): the dynamic of Cu content; (**d**): the dynamic of Z content; (**e**): the dynamic of B content. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in varieties ($p < 0.05$).

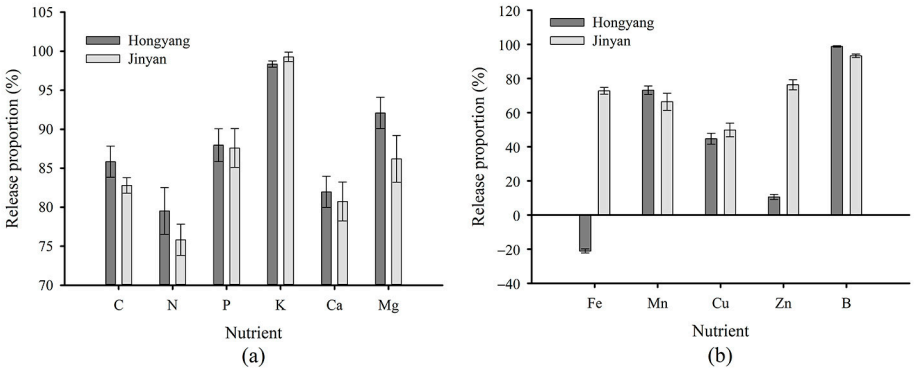

Figure 5. Nutrient releases during litter decomposition and variety differences in the kiwifruit orchard. (**a**): Release proportion of macro-elements; (**b**) release proportion of micro-elements.

3.4. Correlation between Litter Nutrient and Soil Enzyme Activities

Based on the correlation between litter nutrients and soil enzyme activities during litter decomposition, the results showed that Ca content was positively correlated with the protease activity, and the Pearson correlation coefficient was 0.584 ($p < 0.05$) (Figure 7). Furthermore, the results showed that Mg content was negatively correlated with the polyphenol oxidase activity, and the Pearson correlation coefficient was −0.640 ($p < 0.05$). The Mn content was negatively correlated with polyphenol oxidase activity and positively correlated with phosphatase, and the Pearson correlation coefficients were −0.565 and 0.610 ($p < 0.05$), respectively. The origin data of Figures 1–7 were provided in Table S4.

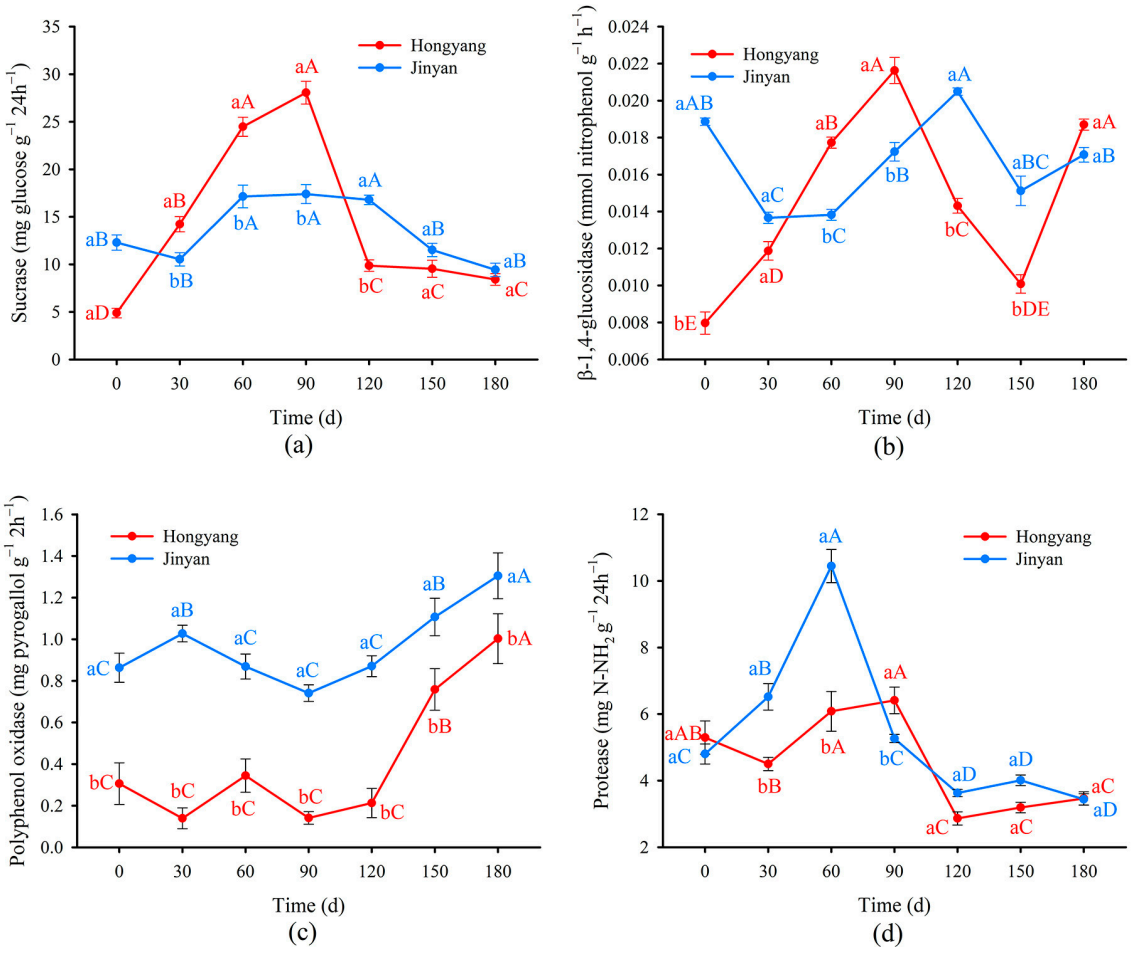

Figure 6. *Cont.*

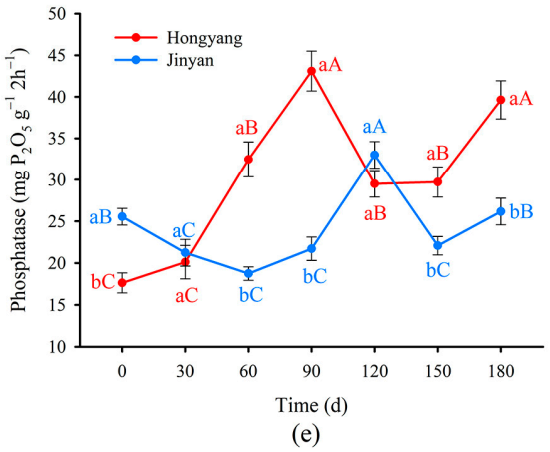

Figure 6. Dynamics of soil enzyme activities during litter decomposition and variety differences in the kiwifruit orchard. (**a**): The dynamic of sucrose activity; (**b**) the dynamic of β-1,4-glucosidase activity; (**c**) the dynamic of polyphenol oxidase activity; (**d**) the dynamic of protease activity; (**e**) the dynamic of phosphatase activity. Different uppercase letters indicate significant differences in decomposition time, and different lowercase letters indicate significant differences in varieties ($p < 0.05$).

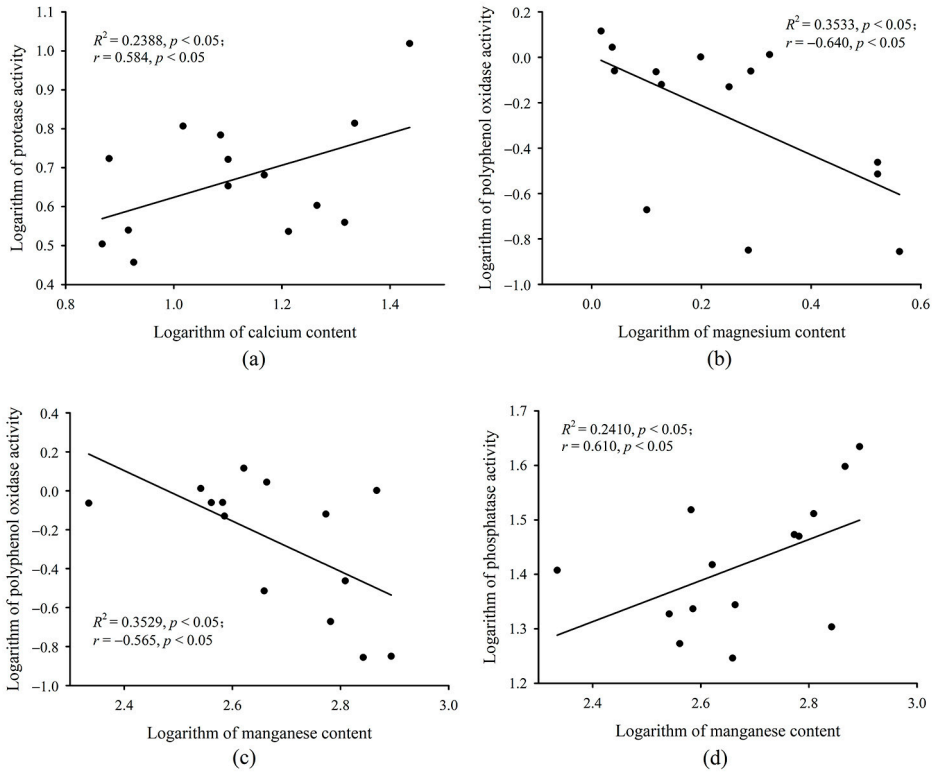

Figure 7. Correlations between litter nutrients and soil enzyme activities during litter decomposition. (**a**): Correlation between Ca and protease; (**b**) correlation between Mg and polyphenol oxidase; (**c**) correlation between Mn and polyphenol oxidase; (**d**) correlation between Mn and phosphatase.

4. Discussion

4.1. Variety Differences in Litter Decomposition

Based on the results of this study, there were significant variety differences between the litter decomposition of the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit. The first was the difference in the decomposition rate. The decomposition rate of the 'Hongyang' kiwifruit litter was significantly faster. The reason is that the initial N content of the 'Hongyang' kiwifruit litter is higher than the 'Jinyan' kiwifruit litter, the C/N and C/P are smaller,

and N/P is lager. In other words, the high substrate quality of the 'Hongyang' kiwifruit litter results in a faster decomposition rate [11,35]. Secondly, during the decomposition process, the N content of the 'Hongyang' kiwifruit litter was higher than that of the 'Jinyan' kiwifruit litter. An adequate nitrogen source ensures the activity of decomposers. In addition, the contents of Mg, Fe, Mn, Cu, and Zn were higher for the 'Hongyang' kiwifruit litter. Finally, in the trend of the soil enzyme activities, the litter of the 'Jinyan' kiwifruit had hysteresis. For example, the turning point of the activities of sucrose, β-1,4-glucosidase, and phosphatase for the 'Hongyang' kiwifruit litter was at 90 days of the decomposition experiment, while that for the 'Jinyan' kiwifruit litter was at 120 days. The turning point of the activities of protease for the 'Hongyang' kiwifruit litter was at 60 days, while that for the 'Jinyan' kiwifruit litter was at 90 days.

There were also some commonalities in the litter decomposition between the 'Hongyang' kiwifruit and 'Jinyan' kiwifruit. These commonalities were mainly reflected in the dynamic trends in the nutrient contents and soil enzyme activities during the litter decomposition process. This is determined by the decomposition mechanism of litter, and the results of this study verified some of the rules, which could provide reference for the study of litter decomposition in orchard ecosystems.

Based on previous studies, faster decomposition causes the disappearance of the organic layer on the soil surface and increases the risk of soil erosion and water loss [36]. In addition, litter decomposition releases a large amount of CO_2, exacerbating global warming. Slower decomposition causes the accumulation of an organic layer, affects the soil water content and permeability, and inhibits the nutrient cycle. Moreover, the litter accumulation can reduce the species diversity by shading, germination inhibition, direct physical interference, and encouraging pathogens [37]. However, these are mostly based on the research results of forest or grassland ecosystems, while the orchard ecosystem has strong human interference, and the amount of litter production in orchard ecosystems is relatively small. For the litter decomposition of the kiwifruit, the half-life period was less than 70 days. At this period, the weight loss of litter reached 50%. With the gradual degradation of sucrose, starch, and cellulose in the litter, its texture softened, and its volume shrunk. Thus, there is no risk of litter accumulation in the orchard. For the problem of soil and water loss caused by the rapid litter decomposition, many agronomic measures could be taken in the orchard, such as planting grass, ploughing the soil, and building drainage facilities. Therefore, there is no negative effect for the decomposition being too fast or too slow in kiwifruit orchards.

4.2. Dynamics of Nutrients during Litter Decomposition

During litter decomposition, the nutrient content is mainly affected by its own characteristics and decomposer activities [38]. For structural elements, such as C, N, P, and Ca, they are the major constituents of plant tissue. The process of the decomposition of the dry matter of litter is also the process of decomposition or synthesis of the compounds composed of these elements. Based on the 'basic stoichiometric decomposition theory', stoichiometric differences between microbial decomposer and decomposition substrates are the driving force of nutrient content changes [39,40]. In other words, if the nutrient content of the substrate cannot meet the physiological needs of the decomposer, the decomposer will immobilize the nutrients in the surrounding environment to the substrate, which will lead to the enrichment of nutrients. Otherwise, the decomposer will use the nutrients of the substrate to complete their own life activities, leading to the decrease in the nutrient content in the substrate. In this study, the content of C during litter decomposition was relative stable at 340 g/kg to 400 g/kg, which indicated that kiwifruit litter could provide sufficient carbon source for decomposers, and C was released gradually with the decomposition of dry matter. N and P are the limiting elements in litter decomposition, and they are the support for microorganisms to consume sugars and cellulose [7]. With the increase in N content in the kiwifruit litter, it reached a peak of about 30 g/kg. The demand of microorganisms for external nitrogen input decreased, and the N content remained relative stable in the late

decomposition stage. The dynamic principle of the P content is similar to that of N, but microorganisms are more sensitive to the P concentration. The P content in the kiwifruit litter fluctuated at a peak of about 3.0 g/kg, which was the reflection to the counterbalance of microbial immobilization and decomposition [41]. The dynamics of the Ca content are often affected by litter dry matter [42]. In the early stage of decomposition (litter lost about 40% of its weight), it was mainly the degradation of small molecular organic matter such as sucrose and starch. The faster release of C compounds led to an increase in the Ca content without altering the real element concentration. After this stage, the structural components of the plant tissue began to degrade, and Ca was released and its content decreased [26]. For nonstructural elements, such as K and Mg, their contents are mainly affected by the combined effect of physical and biological effects [43]. In this study, the content of K during litter decomposition rapidly decreased to 1.0 g/kg and then remained stable, which indicated that K was rapidly lost in the early stage of decomposition via physical leaching. The content of Mg increased first and then decreased, which was similar with Ca. This dynamic trend was consistent with other studies of forest ecosystems [44,45]. The dynamic of the Mg content is influenced by both physics and biology. Microbial immobilization played a vital role in the early stage of the decomposition, which led to an increase in the Mg content. Leaching played a vital role in the later stage, which led to a rapid decrease in the Mg concentration to 1.2 g/kg, which then remained stable [44].

For micro-elements (Fe, Mn, Cu, Zn, B), they are nonstructural elements with less content in plants. In general, they are components of some enzymes or participants in some metabolic activities in plants [46]. During litter decomposition, these elements are affected by many factors, such as physical leaching, chemical synthesis, and biological immobilization [47–49]. In this study, the contents of Fe, Mn, Cu, and Zn during litter decomposition were all rising. Moreover, the content of B increased first and then decreased. Therefore, there was an enrichment of micro-elements, which was observed in other studies [50,51]. Considering the difference in content between the two types of litter, the deposition and adsorption of elements from the environment could be excluded. Thus, it may be the immobilization of the decomposer or the combination with humic acids that leads to nutrient enrichment [50]. In addition, the contents of Fe, Mn, Cu, and Zn in the 'Hongyang' kiwifruit litter were higher than that of the 'Jinyan' kiwifruit litter. The reason may be that the decomposition rate of the 'Hongyang' kiwifruit litter was faster, the humification process was faster, and the organic acids formed more complexes with metals [47]. The dynamic of the B content was similar to that of Ca. In the early stage of decomposition (litter lost about 40% of its weight), the faster release of C compounds led to an increase in the B content without altering the real element concentration. After this stage, the structural components of plant tissue began to degrade, and B content decreased due to leaching [52]. Similarly, due to the faster decomposition rate, B in the 'Hongyang' kiwifruit litter entered the leaching stage earlier. Therefore, the B content in the 'Hongyang' kiwifruit litter was lower than that of the 'Jinyan' kiwifruit litter during the last 150 days of the decomposition experiments.

After 180 days of decomposition experiments, kiwifruit litter released more than 75% of the initial contents of macro-elements. The litter decomposition of the kiwifruit is an important supplement to soil nutrients. However, not all of the nutrients released by litter remain in the soil; some are also released into the atmosphere and water. For example, under the action of microorganisms, the decomposition of litter will release CO_2 and CH_4 into the atmosphere, resulting in the loss of a soil C source [53]. K will be dominated by strong leaching and lost with water flow [54]. Nevertheless, the results of this study have important reference significance.

4.3. The Role of Soil Enzyme during Litter Decomposition

Soil enzymes are important participants in the process of litter decomposition, and the enzymes that play important roles in different decomposition stages are different [55,56]. During litter decomposition, the first stage is the rapid decomposition of easily degradable

substances, including soluble sugars, crude fats, and leaching elements [57]. The second stage is the decomposition of cellulose and hemicellulose, and the final stage is the slow decomposition of stubborn substances such as lignin [7,26,58]. Therefore, sucrose played a major role in the decomposition of soluble sugar, and its activity was higher in the first 90 days of the decomposition experiment. The β-1,4-glucosidase played a major role in the decomposition of cellulose, and its activity was higher from 60 days to 120 days. The polyphenol oxidase played a major role in the decomposition of lignin, and its activity was higher from 120 days to 180 days. In addition, the dynamic trend of soil enzyme activities of the 'Jinyan' kiwifruit showed hysteresis. The reason is that its decomposition rate is slow and there is a lag in the decomposition stage.

Protease and phosphatase are the main enzymes that affect N and P transport during litter decomposition, respectively [59]. In this study, the activities of protease and phosphatase had some correlation with the contents of N and P. For example, protease activity was lower after 90 days, and the N content was stable during this period. The dynamics of phosphatase activity and the P content were both fluctuant. However, there were many inconsistencies between the dynamic trends of the enzyme activities and element contents. On the one hand, it is due to the enrichment of N and P. In other words, decomposers transport N and P from the surrounding environment to the litter, leading to the increase in the element content. On the other hand, the dynamic of N and P contents are not the result of a single enzyme. Some other enzymes, such as urease and leucine aminopeptidase, also affect nitrogen transport [60–62].

Based on previous studies, there is a correlation between nutrient elements and soil enzyme activities during litter decomposition [63,64]. In this study, the contents of Ca, Mg, and Mn were significantly correlated with soil enzyme activities. The mechanism is that the element is a constituent of a substance or an activator of an enzyme. For example, Ca is one of the components of protein, and the Ca content is correlated with protease activity. Mn is one of the components of manganese peroxidase, which is an enzyme that decomposes lignin and has a similar function to polyphenol oxidase [5,65].

5. Conclusions

There are variety differences in the litter decomposition of kiwifruit. Compared with the 'Jinyan' kiwifruit litter, the decomposition rate of the 'Hongyang' kiwifruit litter is significantly faster. The reason is that the litter of the 'Hongyang' kiwifruit has higher initial contents of N and P, higher C/N, higher C/P, and lower N/P. According to the actual situation of the orchard, proper early pruning and ploughing the soil after pruning are the methods to promote litter decomposition. The litter of early pruning has higher initial contents of N and P, and ploughing the soil provides a more humid decomposition environment for litter.

After 180 days of decomposition experiments, the 'Hongyang' and 'Jinyan' kiwifruit litter releases more than 75% of the initial contents of C, N, P, K, Ca, Mg, and B. After conversion, the kiwifruit litter releases more than 107 kg of N, 22 kg of P, and 89 kg of K per hectare. These releases account for about 50% of the nutrients required by kiwifruit trees. Therefore, the litter decomposition of kiwifruit is an important supplement to soil nutrients, especially macro-elements. Orchardists could adjust fertilization measures according to the decomposition process and nutrient release of fruit tree litter. This study could provide a reference for scientific fertilization in kiwifruit orchards and other studies on litter decomposition in orchard ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13030774/s1, Table S1: Physical and chemical properties of the soil of kiwifruit orchard. Table S2: Releases of macro-elements after 180 days of decomposition experiments. Table S3: Releases of micro-elements after 180 days of decomposition experiments. The origin data of Figures 1–7 are provided in Table S4. Reference [66] are cited in Supplementary Materials File

Author Contributions: Conceptualization, Y.L. and X.W.; methodology, Y.L. and Z.G.; investigation, Y.L., J.M., L.C. and X.Z.; data curation, Y.L.; writing—original draft preparation, Y.L.; writing—review and editing, Z.G. and J.M.; supervision, Y.L. and X.W.; project administration, Y.L. and X.W.; funding acquisition, Y.L. and X.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the special project of science and technology of Jiangxi Academy of Sciences (2020YYB05, 2021YSBG21020), the Key R&D Program of Jiangxi Province (20212BBF61006), and the high-end science and technology talents program of Jiangxi Academy of Sciences (2020GDRC1).

Data Availability Statement: The origin data of this study are provided in the supplementary materials.

Conflicts of Interest: On behalf of all authors, the corresponding author states that there are no conflict of interest.

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