Straw Return Decomposition Characteristics and Effects on Soil Nutrients and Maize Yield

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Abstract: Straw return benefits soil nutrient circulation and avoids the environmental pollution caused by incineration. The straw return effect is determined by many factors, such as the returning mode and tillage method. To find the most suitable straw return mode in the hilly areas of south China, we conducted experiments with preceding maize straw in Nanchong (Sichuan Province, China) for three years. Five treatments were tested: (A) rotary tillage without straw return (RT), (B) crushed straw return with rotary tillage (CRT), (C) crushed straw return without rotary tillage (CSR), (D) whole straw return with rotary tillage (WRT), and (E) whole straw return without rotary tillage (WSR). The results indicated that CRT had the fastest decomposition rate, followed by CSR. Moreover, CRT had the fastest nutrient release rates for nitrogen, phosphorus, potassium, cellulose, hemicellulose, and lignin, as well as the highest maize yield (6.62% higher than RT). CRT increased the content of organic matter, total nitrogen, total phosphorus, and total potassium in the soil, as well as improved the soil pH. Furthermore, the numbers of bacteria, Actinomycetes, and fungi in the soil under CRT, CSR, and WSR treatments were higher than under the other two treatments. This study has important reference value for exploring the most favourable straw return method for improving farmland fertility.

Keywords: maize; straw return; decomposition rate; nutrient release; soil fertility; crop yield

1. Introduction

As the by-product of grain harvesting, crop straw is rich in macronutrients, secondary elements, microelements, and organic matter; moreover, it is an important resource for agricultural production [1]. Owing to increased industrial development, farmers often rely on inorganic chemical fertilisers. Furthermore, they discard or burn straw at will, which wastes straw nutrients and causes environmental pollution. In maize production, although more fertiliser can increase yield, this type of land-grabbing management eventually leads to the deterioration of soil structure and properties [2]. Consequently, this mode of production exacerbates soil degradation, making it increasingly difficult to augment maize yield.

In recent years, measures have been proposed and implemented to prohibit straw burning and to encourage the return of straw to fields. Straw return can increase soil fertility and organic matter, as well as improve soil structure, promote soil microbial activity, enhance soil fertiliser retention performance, and it can play a role in regulating field temperature and humidity [3,4]. Straw return can promote crop development, increase yield, improve the quality of agricultural products, save fertiliser input, reduce production costs, and increase farmer income [5,6]. Straw return can increase soil nutrient content and crop yield, which is probably due to the production of enzymes from soil bacteria. Arunrat et al. indicated that amidase, cellulase, and chitinase levels increased with organic matter content, and β-glucosidase, chitinase, and urease levels were positively correlated...
with soil total nitrogen content [7]. Moreover, studies have shown that incorporated rice residues can enhance soil organic carbon, which increases plant biomass [8,9].

However, the straw-returning effect is influenced by many factors, such as the returning mode, crop type, environment, and tillage method [10]. Ji et al. indicated that deep tillage was more effective for increasing enzyme activities in clay, while straw return was more effective in loam [11]. The abundance of soil microorganisms and the activities of most enzymes decrease with an increase in soil depth. Dong et al. revealed that rice straw was more conducive to increasing the contents of ammonium and nitrate than wheat straw [12]. The traditional method of directly returning straw has a low utilisation rate in terms of straw resources. Straw mulching and shallow tillage usually result in the slow decomposition and absorption of nutrients [13]. Moreover, accumulated temperature is an important factor affecting straw decomposition and the release of carbon, nitrogen, and phosphorus. The straw decomposition and nutrient release rates were higher in the summer–autumn stage than in the winter–spring stage [14].

Although there has been ample research on improving the efficiency of straw return in recent years, the various return modes to soil still require further study in relation to changes in soil properties and the influences on crop growth. Most existing studies have focused on only one or two aspects of the straw-returning process, including straw decomposition, straw nutrient release, as well as the changes in soil properties and crop yield. Therefore, this study more comprehensively and systematically analysed the influences and relations of the whole process under five treatments of maize straw return in combination with tillage methods. We hypothesise that crushed straw and rotary tillage is more efficient than whole straw and non-rotary tillage. The objectives of the present study were as follows: (1) to investigate the decomposition and nutrient release rates of straw in the field; (2) to analyse the changes in soil nutrients and microbes after different treatments; and (3) to compare the yield of maize under five different treatments. The results of this study are anticipated to contribute to the scientific knowledge for creating an effective straw return scheme, which will in turn improve farmland fertility and promote sustainable agricultural practices.

2. Materials and Methods

2.1. Experimental Site

Field experiments were carried out from 2020–2022 at the Xianglong Township (105°43′1'' E, 30°56′04'' N), Xichong County, Sichuan Province, China. At the beginning of the experiment, the calcareous purple soil found at the experimental site had a pH of 8.5. The study site has a subtropical, humid monsoon climate with four distinct seasons, an early spring, and sunny winter. The climate is mild, with an average annual temperature of 16.8 °C, and an annual rainfall of 800–1000 mm.

2.2. Experimental Design

Only one summer maize crop was planted annually, all of the straw was returned to the field after harvest, and the experimental data were collected in the third year. The experiment utilised a completely randomised block design every year with five treatments, three replicates, and a 66.67 m² plot. The five treatments were as follows: (A) rotary tillage without straw return (RT), (B) 120 g of dried maize straw being crushed and mixed with 500 g of soil for rotary tillage (CRT), (C) 120 g of dried maize straw being crushed and spread on top of soil without rotary tillage (CSR), (D) 120 g of dried whole maize straw being spread on top of rotating-tilled soil (WRT), and (E) 120 g of dried whole maize straw being spread on top of soil without rotary tillage (WSR). In treatments B–D, the maize straw was packed into 80 mesh nylon bags, and 21 bags were placed in each treatment group for sampling, weighing, and data measurement. The maize variety Xianyu 1171 was sown by hand at the experimental site at a density of 57,000 plants ha⁻¹. A 750 kg/ha compound fertiliser (15-15-15) was used before planting the maize. A total of 80
kg/ha and 120 kg/ha N of fertiliser was used at the elongation and heading stages, respectively. Standard cultivation methods were used for crop management. Diseases and insects were strictly controlled by chemicals to avoid production loss. Herbicides were used to control weeds.

2.3. Straw Decomposition and Nutrient Release Rate Measurement

The decomposition rate and nutrient release rate of straw were determined in the third year of the straw returning to the field. After 0, 20, 40, 60, 80, 100, and 120 days, three bags of straw samples were taken from each treatment site, washed, and dried to weigh the remaining straw. The straw decomposition rate of each treatment at different time points was determined using the following formula: (straw weight before the test − residual straw weight)/straw weight before the test. At the same time, the total nitrogen, phosphorus, potassium, lignin, cellulose, and hemicellulose contents in the straw in the three sample bags were assayed. Total nitrogen, phosphorus, and potassium were determined using the micro-Kjeldahl method [15], colorimetric method [16], and flame photometry technique [17], respectively, as was previously described. Cellulose, lignin, and hemicellulose contents were determined according to the method described by Vax Soest [18]. The straw nutrient content (measured as nutrient content × straw weight) was calculated. Nutrient release rates were determined using the following formula: (straw nutrient content before the test − residual straw nutrient content)/straw nutrient content before the test.

2.4. Soil Nutrient Measurement

The soil layer (0–15 cm) was used to measure the nutrient content before and after treatment. The total nitrogen, phosphorus, and potassium levels were determined as described in Section 2.3. Soil organic matter and pH were measured using the potassium dichromate oxidation method [19] and potentiometric titration method [20], respectively, as previously described. The colonies of bacteria, Actinomycetes, and fungi were counted using the dilution plate method [21]. Each soil sample (10 g) was serially diluted up to 10⁶ dilutions using sterilised distilled water. Then, 1 mL of the desired dilution was added to a Petri dish before the respective sterilised (45 °C) media was poured in. The 10⁻², 10⁻³, and 10⁻⁴ dilutions were used to determine the quantity of soil bacteria, while the 10⁻³, 10⁻⁴, and 10⁻⁵ dilutions were used for quantifying Actinomycetes. For the quantification of fungi, the 10⁻³, 10⁻⁴, and 10⁻⁵ dilutions were used. The poured plates were incubated at 30 ± 2 °C for 24–48 h, as well as for a maximum of 7 days for Actinomycetes. After incubation, the individual colonies were counted, and the colony-forming units (CFU/g) were calculated using the following formula: (number of colonies/volume of sample plated) × Dilution Factor.

2.5. Maize Yield Measurement

The plants obtained from each treatment plot were used to measure the grain yield (moisture content of approximately 14%).

2.6. Data Analysis

SPSS 22.0 (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. Pearson’s correlation analysis was performed using Origin 2022b software (OriginLab, Northampton, MA, USA).

3. Results

3.1. Straw Decomposition Rate

From days 0 to 120, the decomposition rate of maize straw in all treatments increased with time (Figure 1). The decomposition in the CRT and CSR treatments was fast in the early stage and slow in the later stage. For the WRT and WSR treatments, it was slow in
the early stage and fast in the later stage. In the CRT and CSR treatments, the straw decomposition rates between 20 and 40 days were the fastest, increasing by 32.78% and 20.55%, respectively (Figure 1 and Table 1). However, in the WRT and WSR treatments, the fastest decomposition rate was found at 80–100 days, with increases of 16.95% and 10.83% in the decomposition rate, respectively. During the entire experimental period, the decomposition rates of CRT and CSR were significantly higher than those of WRT and WSR, and that of CRT was significantly higher than that of CSR; however, the difference between WRT and WSR was not significant (Table 1). After 120 days of treatment, the decomposition rate of CRT was significantly higher (76.94%) than that of CSR (62.78%), WRT (46.11%), and WSR (42.50%) (Table 1). The results showed that crushing and rotary tillage were more beneficial for the decomposition of maize straw than full straw return and non-rotary tillage.

Table 1. Decomposition rates at time points under different straw return modes.

<table>
<thead>
<tr>
<th>Straw Return Modes</th>
<th>0 d ±</th>
<th>20 d ±</th>
<th>40 d ±</th>
<th>60 d ±</th>
<th>80 d ±</th>
<th>100 d ±</th>
<th>120 d ±</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRT</td>
<td>0.00 ± 0.00 a</td>
<td>11.11 ± 1.27 a</td>
<td>43.89 ± 1.27 a</td>
<td>48.06 ± 0.48 a</td>
<td>57.78 ± 3.76 a</td>
<td>68.61 ± 2.10 a</td>
<td>76.94 ± 2.93 a</td>
</tr>
<tr>
<td>CSR</td>
<td>0.00 ± 0.00 a</td>
<td>9.72 ± 1.73 a</td>
<td>30.27 ± 1.27 b</td>
<td>35.83 ± 0.83 b</td>
<td>43.33 ± 0.83 b</td>
<td>53.06 ± 1.27 b</td>
<td>62.78 ± 1.27 b</td>
</tr>
<tr>
<td>WRT</td>
<td>0.00 ± 0.00 a</td>
<td>2.78 ± 1.73 b</td>
<td>9.72 ± 1.73 c</td>
<td>14.72 ± 2.10 c</td>
<td>18.61 ± 1.27 c</td>
<td>35.56 ± 2.41 c</td>
<td>46.11 ± 2.10 c</td>
</tr>
<tr>
<td>WSR</td>
<td>0.00 ± 0.00 a</td>
<td>1.94 ± 1.27 b</td>
<td>9.17 ± 0.83 c</td>
<td>14.17 ± 3.33 c</td>
<td>21.39 ± 0.48 c</td>
<td>32.22 ± 3.37 c</td>
<td>42.50 ± 3.33 c</td>
</tr>
</tbody>
</table>

Values indicate the mean ± standard deviation, n = 3. Different lowercase letters indicate the significant differences among the different straw return modes at p < 0.05. Abbreviations: CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage.

Figure 1. Decomposition rates of maize straw under different straw return modes. Abbreviations: CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage. Each plotted point represents the mean ± standard deviation of the three samples.
3.2. Straw Nutrient Release Rate

With the extension of the decomposition time, the release rate of the six nutrients in the returning straw gradually increased, although their trends were different (Figure 2). The release rates of the six nutrients were higher in the CRT and CSR treatments than in the WRT and WSR treatments. In the CRT and CSR treatments, the nutrient release rate was high in the early stage (0–40 days) and slow in the later stage (40–120 days) (Figure 2). In contrast, in the WRT and WSR treatments, the nutrient release rate was higher in the late stage (0–80 days) than in the early stage (80–120 days). This was consistent with the change in the decomposition rate of the returned straw among the four treatments.

![Graphs showing nutrient release rates](image)

**Figure 2.** Total nitrogen (A), total phosphorus (B), total potassium (C), cellulose (D), hemicellulose (E), and lignin (F) release rates of maize straw under different straw return modes. Abbreviations: CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage. Each plotted point represents the mean ± standard deviation of the three samples.

For the total nitrogen and total phosphorus releases, the release rate of the CRT treatment was always higher than that of the CSR treatment (Figure 2). However, for total potassium, the release rates of the CRT and CSR treatments increased similarly. WSR led to higher release rates of total nitrogen, total phosphorus, and total potassium than WRT. Throughout the experiment, the release rates of cellulose and lignin were higher in the CRT treatment than in the CSR treatment, whereas the release rates of hemicellulose in the two treatments were similar in the early stage (Figure 2). WRT had higher release rates.
of cellulose, hemicellulose, and lignin than WSR, which was contrary to the release characteristics of total nitrogen, phosphorus, and potassium in these two treatments.

At 120 days after straw decomposition, CRT (75.16%) had the highest total nitrogen release rate, followed by CSR (49.39%), WSR (33.18%), and WRT (22.25%) (Table 2). The release rate of total phosphorus during CRT treatment (73.51%) was significantly higher than that during the CSR (61.76%), WSR (54.23%), and WRT (39.94%) treatments. The total potassium release rates of CRT (64.08%) and CSR (63.03%) were similar and significantly higher than those of WSR (56.50%) and WRT (48.29%). The release rates of cellulose, hemicellulose, and lignin in CRT were significantly higher than those in the other three treatments (Table 2). These results indicate that crushed straw was more beneficial for nutrient release than whole straw. In the crushed straw-returning mode, rotary-tillage promoted an increased nutrient release compared with non-rotary tillage. However, in the whole straw return mode, the use of rotary tillage had different effects on the various nutrient release rates.

Table 2. Nutrient release rates (%) of straw at 120 days of decomposition under different straw return modes.

<table>
<thead>
<tr>
<th>Straw Return Modes</th>
<th>Total Nitrogen</th>
<th>Total Phosphorus</th>
<th>Total Potassium</th>
<th>Cellulose</th>
<th>Hemicellulose</th>
<th>Lignin</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRT</td>
<td>75.16 ± 0.55 a</td>
<td>73.51 ± 0.21 a</td>
<td>64.08 ± 1.28 a</td>
<td>75.43 ± 1.75 a</td>
<td>71.18 ± 1.54 a</td>
<td></td>
</tr>
<tr>
<td>CSR</td>
<td>49.39 ± 0.71 b</td>
<td>61.76 ± 1.10 b</td>
<td>63.03 ± 1.07 a</td>
<td>65.71 ± 1.03 b</td>
<td>55.98 ± 0.93 b</td>
<td></td>
</tr>
<tr>
<td>WRT</td>
<td>22.25 ± 0.77 d</td>
<td>39.94 ± 0.07 d</td>
<td>48.29 ± 1.27 c</td>
<td>55.71 ± 1.03 c</td>
<td>28.89 ± 1.25 c</td>
<td></td>
</tr>
<tr>
<td>WSR</td>
<td>33.18 ± 0.85 c</td>
<td>54.23 ± 2.20 c</td>
<td>56.50 ± 0.18 b</td>
<td>27.36 ± 2.31 d</td>
<td>23.56 ± 0.52 d</td>
<td></td>
</tr>
</tbody>
</table>

Values indicate the mean ± standard deviation, n = 3. Different lowercase letters indicate the significant differences among the different straw return modes at p < 0.05. Abbreviations: CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage.

3.3. Soil Nutrient Content

Table 3 shows the nutrient content of the soil before (CK) and after the five treatments. Compared with CK, all five treatments significantly reduced the soil pH. Rotary tillage without straw reduced the soil pH to some extent. The pH of CRT and CSR was significantly lower than that of RT, although the difference between them was not significant, indicating that crushing straw could further neutralise soil pH. There was also no significant difference between WRT and WSR, indicating that rotary tillage did not affect soil pH when the straw was returned. There was no significant difference in the soil organic matter between the RT and CK groups. The organic matter content of the CRT, CSR, WRT, and WSR treatment groups was significantly higher than that of the CK and RT treatment groups; however, there was no significant difference between the CRT, CSR, WRT, and WSR treatments. This indicates that returning straw to the field can increase soil organic matter content regardless of the method used.
Table 3. Soil nutrient measurements under different straw return modes.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>pH</th>
<th>Organic Matter (g/kg)</th>
<th>Total Nitrogen Content (g/kg)</th>
<th>Total Phosphorus Content (g/kg)</th>
<th>Total Potassium Content (g/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CK</td>
<td>8.53 ± 0.02 a</td>
<td>11.59 ± 0.46 b</td>
<td>0.88 ± 0.03 c</td>
<td>0.62 ± 0.03 c</td>
<td>16.01 ± 0.71 c</td>
</tr>
<tr>
<td>RT</td>
<td>8.39 ± 0.02 b</td>
<td>13.46 ± 0.53 b</td>
<td>0.80 ± 0.02 d</td>
<td>0.53 ± 0.04 d</td>
<td>16.95 ± 0.55 bc</td>
</tr>
<tr>
<td>CRT</td>
<td>8.30 ± 0.02 d</td>
<td>15.61 ± 0.48 a</td>
<td>1.01 ± 0.04 a</td>
<td>0.76 ± 0.04 a</td>
<td>18.76 ± 0.23 a</td>
</tr>
<tr>
<td>CSR</td>
<td>8.32 ± 0.02 d</td>
<td>15.39 ± 0.29 a</td>
<td>0.93 ± 0.02 b</td>
<td>0.76 ± 0.03 a</td>
<td>18.87 ± 0.38 a</td>
</tr>
<tr>
<td>WRT</td>
<td>8.37 ± 0.02 bc</td>
<td>15.00 ± 0.12 a</td>
<td>0.91 ± 0.04 bc</td>
<td>0.64 ± 0.05 bc</td>
<td>17.76 ± 0.34 b</td>
</tr>
<tr>
<td>WSR</td>
<td>8.32 ± 0.03 cd</td>
<td>15.04 ± 0.34 a</td>
<td>0.91 ± 0.03 bc</td>
<td>0.71 ± 0.03 b</td>
<td>17.84 ± 0.30 b</td>
</tr>
</tbody>
</table>

Values indicate the mean ± standard deviation, n = 3. Different lowercase letters indicate significant differences among the different straw return modes at p < 0.05. Abbreviations: CK, straw nutrient content before the test; RT, rotary tillage without straw return; CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage.

Compared with CK, RT had lower total nitrogen and phosphorus content, suggesting that three consecutive years of rotary tillage results in soil nutrient loss, even though there was no significant difference in the total potassium content between them (Table 3). The total nitrogen content of CRT, CSR, WRT, and WSR was significantly higher than that of RT, among which CRT was the highest (1.01 g/kg). CRT and CSR produced the highest soil total phosphorus and potassium contents, followed by WRT and WSR. Similar to CRT and CSR, there were no significant differences between WRT and WSR in terms of total phosphorus and potassium contents.

In short, straw return can neutralise soil pH and increase the content of soil organic matter along with total nitrogen, phosphorus, and potassium regardless of the mode (Table 3). Crushed straw performed better than full straw, except in improving organic matter. Generally, when straw was returned, regardless of whether rotary tillage was performed, there was no obvious effect on soil nutrients.

3.4. Soil Microbial Quantity

The quantities of soil microbes under different straw return modes are listed in Table 4. The bacterial quantities in the CRT, CSR, WRT, and WSR treatments were significantly higher than those in the RT treatment. CRT and CSR produced more bacteria than WRT but produced a comparable number to WSR. Similarly, the numbers of fungi treated with CRT, CSR, WRT, and WSR were significantly higher than those treated with RT. The difference was that the numbers for CRT, CSR, and WSR were higher than those for WRT. For Actinomycetes, CRT, CSR, and WSR were the highest, followed by RT and WRT. The RT treatment produced higher numbers of Actinomycetes than the WRT treatment, which was different from the findings for bacteria and fungi. Finally, the total microbial content of CRT, CSR, and WSR was the highest, followed by that of WRT, which was significantly higher than that of RT. The results showed that straw return could increase the quantity of soil microbes, but the effect of the WRT treatment was relatively weak compared with the other modes.
Table 4. Soil microbial quantity and maize grain yield determination under different straw return modes.

<table>
<thead>
<tr>
<th>Straw Return Modes</th>
<th>Bacteria (10^7 CFU/g)</th>
<th>Fungi (10^4 CFU/g)</th>
<th>Actinomycetes (10^6 CFU/g)</th>
<th>Total (10^7 CFU/g)</th>
<th>Maize Grain Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT</td>
<td>0.97 ± 0.03 c</td>
<td>6.23 ± 0.06 c</td>
<td>6.17 ± 0.19 b</td>
<td>1.59 ± 0.33 c</td>
<td>6.62 ± 0.12 b</td>
</tr>
<tr>
<td>CRT</td>
<td>1.36 ± 0.11 a</td>
<td>7.38 ± 0.06 a</td>
<td>6.59 ± 0.12 a</td>
<td>2.03 ± 0.12 a</td>
<td>7.06 ± 0.10 a</td>
</tr>
<tr>
<td>CSR</td>
<td>1.39 ± 0.07 a</td>
<td>7.79 ± 0.46 a</td>
<td>6.80 ± 0.03 a</td>
<td>2.08 ± 0.08 a</td>
<td>6.92 ± 0.15 ab</td>
</tr>
<tr>
<td>WRT</td>
<td>1.16 ± 0.11 b</td>
<td>6.85 ± 0.15 b</td>
<td>5.82 ± 0.12 c</td>
<td>1.75 ± 0.06 b</td>
<td>6.79 ± 0.05 ab</td>
</tr>
<tr>
<td>WSR</td>
<td>1.28 ± 0.08 ab</td>
<td>7.44 ± 0.17 a</td>
<td>6.75 ± 0.10 a</td>
<td>1.96 ± 0.07 a</td>
<td>6.76 ± 0.27 ab</td>
</tr>
</tbody>
</table>

Values indicate the mean ± standard deviation, n = 3. Different lowercase letters indicate the significant differences among the different straw return modes at p < 0.05. Abbreviations: RT, rotary tillage without straw return; CRT, crushed straw return with rotary tillage; CSR, crushed straw return without rotary tillage; WRT, whole straw return with rotary tillage; and WSR, whole straw return without rotary tillage.

3.5. Maize Yield

Maize grain yields were measured for the five different treatments (Table 4). There was no significant difference in maize grain yield between the CRT, CSR, WRT, and WSR treatments. Additionally, the maize grain yield of RT was significantly lower (6.62%) than that of CRT; however, the difference between RT and the other three treatments was not significant.

3.6. Correlation Analysis

In this study, correlation analyses of the straw decomposition rate (DR), nutrient release rates, soil nutrient characteristics, and maize grain yield (GY) were performed (Figure 3). The DR and nutrient release rates after 120 days of treatment were used for this analysis. The nutrient release rates included total nitrogen (NR), phosphorus (PR), potassium (KR), lignin (LR), cellulose (CR), and hemicellulose (HR). The soil nutrient characteristics included pH (PH), organic matter (OM), total nitrogen content (NC), total phosphorus content (PC), total potassium content (KC), and soil microbial quantity (SM).
The results in Figure 3 show that there was no significant correlation between the DR and nutrient release rate, except for a significant positive correlation \((p < 0.05)\) with KR. NR, PR, KR, LR, CR, and HR were significantly and positively correlated \((p < 0.01)\). PR, KR, and HR were significantly and positively correlated with OM, and KR was positively correlated with KC and GY \((p < 0.05)\). Moreover, DR, OM, NC, PC, KC, SM, and GY had significant or extremely significant positive correlations with each other, indicating that the higher the decomposition rate of the returned straw, the higher the nutrient content in the soil, as well as the higher the maize grain yield. In addition, there was a significant negative correlation \((p < 0.01)\) between the pH and the seven values of DR, OM, NC, PC, KC, SM, and GY. This indicates that the higher the decomposition rate of straw, the lower the soil pH. Therefore, the returning straw had a neutralising effect on the alkaline soil used in this study. A decrease in soil pH led to an increase in soil nutrients, soil microbes, and grain yield.
4. Discussion

4.1. Different Effects of Straw Return Modes on Different Investigation Items

In this study, we investigated the decomposition rates, nutrient release rates, soil pH, soil nutrient content, soil microbial quantity, and maize yield under different straw return modes. The results showed that, compared with WRT and WSR, CRT and CSR resulted in higher decomposition rates, nutrient release rates, and soil nutrient contents, as well as in lower soil pH (Tables 1–3 and Figures 1 and 2). This suggests that crushed straw releases nutrients and improves soil fertility more efficiently than intact straw, which is consistent with previous research results [22,23]. Previous research has shown that the crushed straw notably increased both the release of nitrogen release and the peroxidase activity compared to intact straw [23,24]. However, soil microbial quantities were comparable among the CRT, CSR, and WSR treatments, and there were no significant differences in the maize yields between the CRT, CSR, WRT, and WSR treatments (Table 4). This finding could be attributed to the fact that soil microbial quantities and maize yield are affected by a combination of complex factors. First, soil microbes exhibit seasonal dynamics [25] as the soil microbial counts and the ratio of fungi and bacteria in the wet season were higher than those in the dry season. Soil physical properties, soil total nitrogen, soil organic carbon, soil water content, and soil organic carbon–nitrogen ratio affect the counts and community structure of soil microorganisms to different degrees [26]. The maize variety and climatic factors played critical roles in terms of increasing yield [27]. However, cultivation measures—including irrigation, fertilisation, sowing density, sowing date, and harvest time—could change the contribution rates of maize variety and climatic conditions [28].

In addition, compared with CSR, CRT had a higher straw decomposition rate and nutrient release rate (except for potassium) (Tables 1 and 2 and Figures 1 and 2). It seems that rotary tillage is more beneficial for straw decomposition and nutrient release than non-rotary tillage when crushed straw is returned to the field, which is consistent with the results of a previous study [29]. Tian et al. found that rotary tillage had a higher straw decomposition rate; higher release rates of carbon, nitrogen, phosphorus, and potassium; and a comparable total phosphorus and potassium content than no tillage [30]. In the treatment of no-tillage straw return, the straw was exposed to air but lacked sufficient contact with soil and water; therefore, the activity of soil enzymes and microbes was low, and the decomposition strength of the straw was small. In comparison, a study on rotary tillage showed that the crushed straw and soil were fully mixed and the soil was well ventilated and permeable; furthermore, the temperature of the 0–20 cm layer of soil was higher than that of the surface, which is conducive to the decomposition of straw by soil microbes, thus promoting the decomposition of straw [31]. Nevertheless, there was no significant difference between CRT and CSR, or between WRT and WSR in increasing soil nutrient content and improving pH (Table 3), thus suggesting that the influence of rotary tillage on these two investigation items was less than that of crushing.

4.2. Relationship between Decomposition Rate, Nutrient Release Rate, and Soil Nutrient Content

This study found no significant correlation between the straw decomposition rate and nutrient release rate (except for potassium) (Figure 3). This indicates that a high degree of straw decomposition does not necessarily result in a high nutrient release rate. Microbial activity is primarily responsible for the breakdown of straw [32]. The decomposition rate of straw increases with time, and the process is usually divided into a rapid decomposition stage and slow decomposition stage [33]. In the rapid stage, the decomposition of soluble organic compounds greatly reduces the quality of straw. In the slow stage, substances that are not decomposed or are not utilised by microorganisms are slowly decomposed through physical and chemical actions. The crushed straw return in this study conformed to a decomposition law reported previously (Figure 1). The process of nutrient release was affected by the straw return mode, and different nutrient releases
follow different rules [34]. The difference in the short-term nutrient release rates was related to the states of the nutrients in straw [35]. Potassium exists mainly in the ionic state and is soluble in water, thus causing it to have the fastest release. More than 60% of phosphorus exists in the ionic state, while the other parts exist mainly in the organic form; however, the organic acids secreted by roots can promote the decomposition and release of phosphorus [36]. Nitrogen is mainly present in an insoluble organic form, thus making it have a slow release [33]. Therefore, the nutrient release rates of straw are as follows (highest first): potassium > phosphorus > nitrogen. In this study, the nutrient release rates of CSR, WRT, and WSR were consistent with this rule, while the release rate of potassium in CRT was lower than that of the other two nutrients (Table 2). The dual action of crushing and rotary tillage may lead to a faster release of nitrogen and phosphorus.

There was also no significant association between the nutrient release rates and soil nutrient content (except for KR and KC). This indicates that a high nutrient release rate does not necessarily result in a high soil nutrient content. It has been reported that soil nutrients may be lost owing to different tillage methods, even those with high straw release [37]. For example, long-term rotary tillage resulted in a decrease in the available soil phosphorus and potassium [38]. However, there was an extremely significant positive correlation between the straw decomposition rate and soil nutrient content (Figure 3). Therefore, the straw decomposition rate remains a criterion for achieving high soil nutrient content, even though the nutrient release rate is not significantly related to it.

5. Conclusions

In this study, the decomposition rates, nutrient release rates, soil pH, soil nutrient content, soil microbial quantity, and maize yield were investigated under five different straw return modes. According to the results, we drew the following conclusions: (1) The decomposition and nutrient release rate of maize straw increased with time in all treatments. CRT treatment showed the highest decomposition and nutrient release rate; (2) CRT achieved the highest soil total nitrogen content, while CRT and CSR generated soil with higher total phosphorus and potassium contents than WRT and WSR. All four treatments enhanced soil organic matter and neutralised soil pH; and (3) The quantities of soil bacteria, fungi, Actinomycetes, and total microbes in CRT, CSR, and WSR were higher than those in WRT and RT. Although there was no significant difference between CRT and the other three treatments, the maize grain yield of CRT was significantly greater (6.62%) than that of RT. Therefore, as CRT performed well in the above aspects, it can be applied as a favourable scheme in the maize-planted hilly areas of south China in terms of improving farmland fertility. However, this study lacks data on soil bulk density and soil enzyme activity, as well as on available soil nitrogen, phosphorus, and potassium, which—in importantly—influence soil fertility and crop growth. Therefore, further studies of these variables are required for straw return research.

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