

Postprint: Decomposition Characteristics and Nutrient Release Patterns of Different Crop Straws in Upland and Paddy Fields

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Abstract

Using rice, wheat, and maize straw as well as rape and broad bean green stalks as experimental materials, this study employed the nylon mesh bag method to investigate the decomposition characteristics and nutrient release patterns of different straw types after incorporation into upland and paddy fields, aiming to provide a theoretical basis for agricultural straw recycling and return-to-field techniques in purple hilly regions. The results indicated that following straw incorporation, the decomposition rates of all five straw types exhibited a rapid initial phase (0-60 days) followed by a slower later phase (60-360 days). After 360 days of decomposition, cumulative straw decomposition rates in upland fields ranged from 52.88% to 75.80%, displaying the trend of rape > rice > maize > wheat > broad bean, with broad bean green stalks showing significantly lower cumulative decomposition rates compared to the other straw types. In paddy fields, cumulative straw decomposition rates ranged from 45.01% to 62.12%, following the trend of rice > maize > wheat > rape > broad bean. Nutrient release rates from the five straw types in both upland and paddy fields consistently followed the pattern of potassium > phosphorus > nitrogen > carbon. At the experimental endpoint, carbon, nitrogen, phosphorus, and potassium release rates from straw in upland fields were 65.50%-87.37%, 54.64%-69.72%, 89.65%-98.96%, and 79.92%-96.63%, respectively, with rape straw exhibiting higher nutrient release rates than the other four straw types. In paddy fields, the corresponding ranges were 49.95%-69.57% for carbon, 32.89%-77.11% for nitrogen, 90.70%-96.80% for phosphorus, and 77.45%-90.47% for potassium. Overall, both cumulative decomposition rates and nutrient release rates of straw were higher in upland soils than in paddy fields; rape and rice straw decomposed more readily in upland conditions, whereas rice and maize straw decomposed more readily in paddy conditions; potassium release rates from straw were notably high.

Full Text

Preamble

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Nutrient release patterns and decomposition characteristics of different crop straws in drylands and paddy fields*

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Abstract: To provide a theoretical basis for crop straw recycling and straw utilization in agricultural fields, the decomposition characteristics and nutrient release patterns of different crop straws [rice, wheat, corn, rapeseed (green stalk) and broad bean (green stalk)] were studied using the nylon net bag method in drylands and paddy fields. The results showed that the decomposition rate of straw was high in the early phase (0-60 d) and then dropped in the later phase (60-360 d). After 360 d, the cumulative decomposition rates of straw were 52.88%-75.80% and 45.01%-62.12% in drylands and paddy fields, respectively. The cumulative decomposition rate of broad bean was significantly lower than that of other crops in both fields. Furthermore, rapeseed and rice decomposed faster in drylands and paddy fields. At the endpoint of the experiment, the sequence of nutrient release rate of straw in the two fields was $K > P > N > C$. The rate of carbon release by rice, corn, wheat, rapeseed and broad bean straws was up to 87.37% in dryland and 69.57% in paddy field. The rates of carbon release by rapeseed and rice were significantly higher than those of other crop straws in dryland and paddy field. The average rate of nitrogen release by the five straws tracked the following trend: broad bean (69.72%) > rice (68.45%) > rapeseed (63.60%) > corn (57.28%) > wheat (54.64%) in dryland. The rate of nitrogen release by broad bean was the highest (77.11%) in the paddy field. The rates of release of phosphorus by straw were 89.65%-98.96% and 90.70%-96.80% in dryland and paddy field, respectively. Then the rate of release of phosphorus by wheat was persistently lower than that of any other straw in both fields. The rate of release of potassium by rapeseed was respectively 20.91%, 5.84%, 6.67% and 5.19% higher than that of wheat, rice, corn and broad bean in dryland. Also the rate of release of potassium by wheat was significantly lower than the others. Overall, the decomposition and nutrient release rates in dryland were higher than those in paddy field. Rapeseed green straw in dryland, and rice and maize straws in paddy field were more easily decomposed than other crops straws. The release rate of potassium was highest in all the tested elements.

Keywords: Crop straw; Decomposition characteristic; Nutrients release; Dryland; Paddy field

Introduction

China is a major agricultural nation, producing over 800 million tons of crop straw annually [1]. Straw is rich in organic carbon, nitrogen, phosphorus, potassium, and micronutrients, making it an important biological resource. However, the utilization rate of straw in China is low, with effective return-to-field rates of less than one-third [2]; most straw is burned or discarded, causing not only tremendous resource waste but also serious ecological environmental impacts that affect human quality of life [3]. Therefore, the rational utilization of crop straw has become an urgent agricultural issue. Previous studies have shown that returned straw decomposes through the combined action of microorganisms and enzymes [4-5], which not only improves soil physical properties [6] but also releases nutrients such as nitrogen, phosphorus, and potassium for plant uptake, thereby enhancing soil fertility [7]. In recent years, to address agricultural resource waste and mitigate soil degradation and agricultural non-point source pollution caused by excessive fertilizer application [8-10], utilizing the nutrient release from decomposed straw and other agricultural wastes to reduce chemical fertilizer use has become a focus of attention among scholars both domestically and internationally [11-15].

Previous research has extensively investigated the decomposition patterns of returned straw. Li et al. [16] found that decomposition rates varied with burial depth, with 5 cm depth showing the fastest decomposition, followed by 15 cm depth, while surface coverage was the slowest. Zhang et al. [17] discovered that tillage methods significantly affect straw decomposition patterns, with decomposition rates following the order: plow tillage > rotary tillage > no-tillage. Abro et al. [18] noted that lower temperatures favor the retention and conservation of organic carbon and microbial biomass carbon and nitrogen in straw, whereas higher temperatures accelerate the mineralization of organic carbon in straw. Tang et al. [19] found through studies on ^{14}C -labeled straw degradation under different moisture conditions that rice straw decomposition rates were significantly higher under flooded conditions than in dryland. Dai et al. [15] reported that different straw types exhibited varying decomposition rates, with rapeseed straw decomposing faster than rice and wheat straws during the rapid decomposition phase, possibly due to differences in straw tissue structure.

Researchers have also conducted numerous studies on nutrient release patterns from returned straw, though results have not been entirely consistent. Some studies found that the release rate of nitrogen, phosphorus, and potassium from returned straw followed the order: potassium > phosphorus > nitrogen [20], while others indicated that phosphorus showed the highest release rate, followed by nitrogen, with potassium being the lowest [21]. Currently, most research has focused on the effects of single land use patterns [22-23] or single crop growth periods [24-25] on straw decomposition characteristics, with limited straw types

examined [26]. Studies on straw return decomposition characteristics under different land use patterns in the purple hilly region remain scarce. Therefore, this study employed the nylon net bag method to investigate the annual decomposition characteristics and nutrient release patterns of different returned straw types under different land use patterns in the purple hilly region, using common crop straws [rice (*Oryza sativa*), rapeseed (*Brassica campestris*), maize (*Zea mays*), broad bean (*Vicia faba*), wheat (*Triticum aestivum*)] as research objects, aiming to provide a theoretical basis for agricultural straw recycling and straw return technology determination in this region.

1. Materials and Methods

1.1 Experimental Site Overview

The experiment was conducted at the National Purple Soil Fertility and Fertilizer Efficiency Monitoring Station, located at the Southwest University Experimental Farm in Beibei District, Chongqing (30°26 N, 106°26 E). The region belongs to the purple hilly area with a square-hill and shallow-gully topography at an elevation of 266.3 m. The climate is subtropical monsoon, with an average annual temperature of 18.4 °C, annual precipitation of 1,105.5 mm, and sunshine duration of 1,276.7 h. During the experimental year (2014), the average summer temperature was 21.6 °C and winter temperature was 14.2 °C, with high temperatures concentrated in July and August and rainfall mainly concentrated in summer and winter. Light winds prevailed throughout the year. The test soil was purple soil developed from Jurassic Shaximiao Group purple mud shale, classified as neutral purple soil subtype, gray-brown purple mud. The basic physical and chemical properties of the test soil are shown in Table 1 .

1.2 Test Straw Materials

In May 2014, five types of mature crop straw (rice straw, wheat straw, maize straw, rapeseed green stalk, and broad bean green stalk) were collected from rural areas around Southwest University in Beibei District, Chongqing. The samples were washed in the laboratory, and the rapeseed and broad bean green stalks were heat-treated (kill-green), then all samples were air-dried and cut into 5-8 cm pieces before being oven-dried at 60 °C to constant weight. One portion was preserved for the return-to-field experiment, while another portion was ground to pass through a 1 mm sieve for nutrient content determination. The basic properties of the straw samples are shown in Table 2 .

1.3 Experimental Design

The experiment selected two soil types: dryland (D) and paddy field (P). The dryland cropping system was maize-rapeseed intercropping, while the paddy field system was rice-wheat rotation. Local main cultivars were used for all crops. During crop growth, nitrogen, phosphorus, and potassium fertilizers were applied as urea, calcium superphosphate, and potassium sulfate, respectively.

For rice and wheat cultivation, 60% of nitrogen fertilizer and all phosphorus and potassium fertilizers were applied as base fertilizer, with the remaining 40% nitrogen applied as topdressing. For maize and rapeseed cultivation, 50% of nitrogen fertilizer and all phosphorus and potassium fertilizers were applied as base fertilizer, with the remaining 50% nitrogen applied as topdressing. Crop varieties, planting times, and fertilization rates are shown in Table 3 .

Approximately 10 g of 5–8 cm pieces of rice straw (D-SD, P-SD), wheat straw (D-XM, P-XM), maize straw (D-YM, P-YM), rapeseed green stalk (D-YC, P-YC), and broad bean green stalk (D-CD, P-CD) were placed separately in pure nylon bags with 40-mesh aperture, constituting 10 treatments. Three 5 m × 5 m plots were randomly selected in both paddy field and dryland. On May 30, 2014, the nylon bags containing straw were buried in the plots at a depth of 5 cm. Each plot contained seven bags of each of the five straw types, with 1 m spacing between different straw burials. Samples were collected on days 10, 30, 60, 90, 150, 240, and 360 after burial. During each sampling, one bag of each straw type was randomly removed from each plot. The mud adhering to the bags was rinsed off with tap water, followed by three washes with distilled water. The samples were then oven-dried at 60 °C to constant weight, weighed, ground to pass through a 1 mm sieve, and analyzed for carbon, nitrogen, phosphorus, and potassium content to calculate nutrient release rates.

1.4 Sample Analysis and Data Processing

1.4.1 Sample Measurement The decomposition rate (%) was calculated as $(M_0 - M_t) / M_0 \times 100\%$ (1), and the cumulative nutrient release rate (%) as $(M_0 \times C_0 - M_t \times C_t) / M_0 \times C_0$ (2). Basic physical and chemical properties of soil were determined using conventional analytical methods [27]. Straw organic carbon was measured using the potassium dichromate volumetric method with external heating. After digestion with $H_2SO_4-H_2O_2$ solution, straw total nitrogen content was determined by the Kjeldahl method, total phosphorus by the vanadium-molybdenum yellow colorimetric method, and total potassium by flame photometry [28].

1.4.2 Data Processing The formulas for calculating cumulative straw decomposition rate and cumulative nutrient release rate [23] are as follows:

where M_0 is the initial dry weight of added straw (g), M_t is the straw dry weight at decomposition time t (g), t is decomposition time (d), C_0 is the initial nutrient content of straw ($g \cdot kg^{-1}$), and C_t is the nutrient content of straw at decomposition time t ($g \cdot kg^{-1}$).

Data were processed using Microsoft Excel 2010 and SPSS 20.0 software. LSD test and t-test were used to examine experimental data ($P < 0.05$), and Microsoft Excel 2010 was used for graphing.

2. Results

2.1 Decomposition Characteristics of Different Straw Types in Dryland and Paddy Field

As shown in Figure 1a [Figure 1: see original paper], the cumulative decomposition rates of all five crop straw types in dryland soil increased with decomposition time, exhibiting a pattern of rapid decomposition in the early stage followed by a slower rate later. For D-XM and D-SD, the rapid decomposition period was 0–60 d, with average decomposition rates of $0.091 \text{ g} \cdot \text{d}^{-1}$ and $0.095 \text{ g} \cdot \text{d}^{-1}$, respectively; the slow period was 90–360 d, with cumulative decomposition rates reaching 67.02% and 74.23%, respectively. D-YC and D-CD showed rapid decomposition during 0–30 d, with cumulative decomposition rates of 44.55% and 40.64% at 30 d, respectively, which were significantly higher than those of D-XM, D-SD, and D-YM (Table 4). For D-YM, the rapid decomposition period was 0–10 d with a decomposition rate of $0.138 \text{ g} \cdot \text{d}^{-1}$, while the slow period was 30–360 d with decomposition rates ranging from 0.020 to $0.064 \text{ g} \cdot \text{d}^{-1}$.

The cumulative decomposition rates of the five returned straw types reached their highest values at the end of the experiment, following the order: D-YC (75.80%) > D-SD (74.23%) > D-YM (69.34%) > D-XM (67.02%) > D-CD (52.88%), with D-CD being significantly lower than the other four straw types (Table 4).

As shown in Figure 1b, the decomposition patterns of the five crop straw types in paddy field soil were similar to those in dryland soil, also showing rapid decomposition in the early stage followed by gradual stabilization. However, the rapid decomposition periods differed from those in dryland soil. For P-XM and P-YM, the rapid decomposition period was 0–90 d. The decomposition rate of P-XM reached 38.09% at 10 d after burial and gradually increased thereafter, reaching its maximum cumulative decomposition rate of 54.12% at 90 d. In contrast, P-YM achieved a cumulative decomposition rate of 59.45% at 90 d, which was 9.84% higher than that of P-XM.

P-SD, P-YC, and P-CD had rapid decomposition periods of 0–60 d, with cumulative decomposition rates of 55.75%, 46.82%, and 49.09% at 60 d, respectively, with P-SD being significantly higher than P-YC and P-CD (Table 4). All five straw types decomposed fastest during 0–10 d, with decomposition rates of $0.382 \text{ g} \cdot \text{d}^{-1}$, $0.299 \text{ g} \cdot \text{d}^{-1}$, $0.228 \text{ g} \cdot \text{d}^{-1}$, $0.325 \text{ g} \cdot \text{d}^{-1}$, and $0.361 \text{ g} \cdot \text{d}^{-1}$ for P-XM, P-SD, P-YM, P-YC, and P-CD, respectively. The cumulative decomposition rates during this period accounted for 78.34%, 46.84%, 35.18%, 64.36%, and 77.29% of the final experimental values, respectively. At the end of the experiment, the cumulative decomposition rates followed the order: P-SD > P-YM > P-XM > P-YC > P-CD, with P-SD being significantly greater than the other four straw types (Table 4).

Additionally, decomposition rates of returned straw differed between dryland

and paddy field soils. P-XM reached its maximum cumulative decomposition rate of 54.12% at 90 d, which was 1.35 times that of D-XM at 90 d but significantly lower than D-XM's maximum cumulative decomposition rate of 67.02% achieved at 360 d (Table 4). P-SD, P-YM, and P-YC achieved their maximum decomposition rates of 62.12%, 60.59%, and 48.58% at the end of the experiment, respectively, which were 83.68%, 87.38%, and 64.08% of the maximum cumulative decomposition rates of the same straw types in dryland soil. At the end of the experiment, the cumulative decomposition rates of D-XM, D-SD, D-YM, D-YC, and D-CD in dryland soil were all higher than those in paddy field soil, being 1.37, 1.19, 1.14, 1.56, and 1.17 times greater, respectively. These results indicate that dryland soil is more conducive to the decomposition of wheat, rice, maize, rapeseed, and broad bean straw.

Carbon Release Characteristics

The carbon release characteristics of the five returned straw types in dryland and paddy field are shown in Figure 2 [Figure 2: see original paper]. Cumulative carbon release rates varied among different straw types and between dryland and paddy field soils.

As shown in Figure 2a, the cumulative carbon release rates of the five straw types in dryland soil generally exhibited a trend of rapid increase followed by slow increase, with inflection points occurring at 60–90 d. At these inflection points, cumulative carbon release rates ranged from 52.99% to 70.60%. For D-XM, the carbon release rate was 40.32% at 10 d, with 0–60 d being the rapid carbon release period; after 60 d, the carbon release rate increased slowly, reaching a maximum of 75.98% at the end of the experiment. D-SD, D-YM, and D-YC achieved rapid carbon release within 0–90 d, with cumulative release rates of 66.02%, 63.45%, and 70.6% at 90 d, respectively, accounting for 89.34%, 85.22%, and 80.81% of their maximum carbon release amounts in dryland soil. Throughout the decomposition process, the cumulative carbon release of D-XM, D-SD, D-YM, D-YC, and D-CD all reached maximum values after 360 d of decomposition, following the order: D-YC > D-XM > D-YM > D-SD > D-CD, with D-YC's cumulative carbon release being significantly higher than the other four straw types (Table 5), at 1.14, 1.18, 1.17, and 1.33 times that of D-XM, D-YM, D-SD, and D-CD, respectively.

As shown in Figure 2b, the cumulative carbon release rates of the five straw types in paddy field also exhibited a pattern of rapid increase followed by slow increase with decomposition time, with rapid carbon release during 0–60 d and slow release during 60–360 d. After 60 d of decomposition, the cumulative carbon release rates of P-XM, P-SD, P-YM, P-YC, and P-CD were 50.92%, 62.13%, 43.84%, 47.93%, and 51.86%, respectively, accounting for 80.91%, 89.31%, 66.72%, 92.19%, and 84.12% of their maximum cumulative carbon release amounts. Although P-YM had lower carbon release than the other four straw types during the rapid release period, its carbon release exceeded the others at 90 d and 240 d, being 10.72%, 8.75%, 26.24%, and 8.02% higher than P-XM, P-SD, P-YC, and P-CD, respectively, at 240 d. At the end of the

experiment, P-SD showed significantly higher carbon release than the other four straw types, following the order: P-SD (69.57%) > P-YM (65.70%) > P-XM (52.51%) > P-YC (51.99%) > P-CD (49.95%).

The carbon release patterns of returned straw also varied under different land use patterns. During 0–10 d, carbon release rates among the five straw types showed little difference, with all except rapeseed straw exhibiting higher release rates in paddy field than in dryland. Wheat straw reached its maximum cumulative carbon release rate at 150 d in paddy field soil, while it reached its maximum at 360 d in dryland soil, with the rate being significantly higher than that in paddy field soil (Table 5). Throughout the experimental period, straw showed higher cumulative carbon release in dryland soil than in paddy field soil. At the end of the experiment, the cumulative carbon release amounts of wheat, rice, maize, rapeseed, and broad bean straw in dryland soil were 44.69%, 6.21%, 13.31%, 68.05%, and 31.13% higher than those in paddy field soil, respectively, possibly due to stronger microbial activity in dryland that promoted greater carbon release from straw.

Nitrogen Release Characteristics

As shown in Figure 3 [Figure 3: see original paper], nitrogen release characteristics were generally similar to carbon but with some differences. Figure 3a shows that during the decomposition process of the five tested straw types buried in dryland soil, the cumulative nitrogen release rate generally exhibited a trend of rapid increase followed by slow decrease with decomposition time. D-YC showed no obvious inflection point throughout the decomposition process; its cumulative nitrogen release rate was 29.95% at 10 d and reached a maximum of 63.60% at 360 d, which was 4.02, 2.19, 2.07, 1.36, and 1.95 times the cumulative release rates at 30 d, 60 d, 90 d, 150 d, and 240 d, respectively. D-XM, D-SD, D-YM, and D-CD achieved rapid nitrogen release during 0–30 d, with rates ranging from 52.30% to 76.62%. At the end of the experiment, the five straw types showed significant differences in cumulative nitrogen release rates, following the order: D-CD (69.72%) > D-SD (68.45%) > D-YC (63.60%) > D-YM (57.28%) > D-XM (54.64%), with D-XM being significantly lower than the other four straw types (Table 6).

As shown in Figure 3b, the rapid nitrogen release period for the five straw types was 0–30 d, with a slow release period of 60–360 d. During the rapid release period, nitrogen release rates followed the order: P-YC > P-SD > P-CD > P-YM > P-XM, with P-YC's nitrogen release rate being 1.21 times that of P-XM. At the end of the experiment, the five tested straw types showed significant differences in cumulative nitrogen release rates (Table 6), with broad bean straw having the highest nitrogen release rate at 77.11%, followed by rice straw at 64.15%, and rapeseed straw the lowest at only 32.89%. The cumulative nitrogen release rates of wheat, rice, maize, rapeseed, and broad bean straw accounted for 70.98%, 100%, 86.43%, 52.39%, and 95.99% of their respective straw nitrogen contents.

Nitrogen release characteristics of returned straw differed between dryland and paddy field soils. After 30 d of burial and decomposition, rapeseed straw showed a cumulative nitrogen release rate of 62.77% in paddy field soil but only 15.82% in dryland soil, accounting for just 25.20% of the paddy field value. After 360 d of decomposition, wheat straw had a cumulative decomposition rate of 54.64% in dryland, which was 1.48 times that in paddy field. Overall, at the end of the experiment, the five tested straw types showed greater cumulative nitrogen release rates in dryland than in paddy field, likely due to greater straw decomposition amounts in dryland soil.

2.4 Phosphorus Release Characteristics of Different Straw Types in Dryland and Paddy Field

As shown in Figure 4 [Figure 4: see original paper], phosphorus release rates after straw decomposition showed a pattern of rapid increase in the early stage followed by basic stability in the later stage, which was distinctly different from carbon and nitrogen release patterns. Figure 4a shows that after straw burial and decomposition in dryland, 0–60 d was the rapid phosphorus release period, with cumulative phosphorus release rates of 83.95%, 95.59%, 95.64%, 97.22%, and 95.68% for D-XM, D-SD, D-YM, D-YC, and D-CD, respectively, with wheat straw's cumulative phosphorus release rate being significantly lower than the other four straw types (Table 7). The period of 60–360 d was a stable release phase, during which the cumulative phosphorus release rates of all five straw types showed little change. At the end of the experiment, phosphorus cumulative release rates ranged from 89.65% to 98.96%, following the order: D-YC > D-YM > D-SD > D-CD > D-XM. Throughout the entire experiment, D-XM straw consistently showed lower cumulative phosphorus release rates than the other four straw types, which may be related to the structural characteristics of the straw itself.

As shown in Figure 4b, phosphorus release characteristics of straw in paddy field were similar to those in dryland, with 0–60 d being the rapid release stage during which nearly complete phosphorus release from straw was achieved, as straw decomposition amounts were minimal during 60–360 d. During the rapid decomposition stage, the five straw types showed little difference in cumulative phosphorus release rates, ranging from 92.04% to 97.16%. At the end of the experiment, the difference in cumulative phosphorus release rates among the five straw types was only 6.10%, but reached a significant level (Table 7), with P-YM showing the highest cumulative phosphorus release rate at 96.50%, which was 6.73%, 2.11%, 0.31%, and 1.49% higher than P-YC, P-CD, P-SD, and P-XM, respectively.

The phosphorus release characteristics of straw in both dryland and paddy field achieved nearly complete phosphorus release after 60 d of decomposition. However, cumulative phosphorus release rates differed between dryland and paddy field. For wheat straw, the cumulative phosphorus release rate was 92.04% in paddy field after 60 d of decomposition, which was 9.64% higher than that in

dryland. After 10 d of decomposition, phosphorus release rates in paddy field were greater than those in dryland, with increases ranging from 3.05% to 25.21% among the five straw types. At the end of the experiment, there was no significant difference in cumulative phosphorus release rates between dryland and paddy field soils.

2.5 Potassium Release Characteristics of Different Straw Types in Dryland and Paddy Field

As shown in Figure 5 [Figure 5: see original paper], potassium release characteristics of straw were similar to phosphorus, with cumulative potassium release rates reaching relatively high values during the rapid release period and showing little change in later stages. Figure 5a shows that D-YC exhibited an inflection point at 60 d of decomposition, while D-XM, D-SD, D-YM, and D-CD showed inflection points at 30 d. The cumulative potassium release rates at these inflection points showed little difference, ranging from 89.39% to 99.06%. During the stable release stage, D-XM's cumulative potassium release rate was significantly lower than the other four straw types ($P < 0.05$). At the end of the experiment, D-YC had the maximum cumulative potassium release rate at 96.63%, which was 20.91%, 5.84%, 6.67%, and 5.19% higher than D-XM, D-SD, D-YM, and D-CD, respectively.

As shown in Figure 5b, the rapid potassium release period for the five straw types in paddy field was 0-30 d, with 60-360 d being the stable release period. After 30 d of decomposition, the cumulative potassium release rates of P-XM, P-SD, P-YM, P-YC, and P-CD were 96.54%, 95.53%, 96.30%, 99.03%, and 98.66%, respectively. After 150 d of decomposition, the cumulative potassium release rates showed a slight decreasing trend. At the end of the experiment, P-XM, P-SD, P-YM, P-YC, and P-CD accounted for 80.22%, 92.33%, 88.73%, 91.20%, and 91.69% of their maximum cumulative potassium release rates, respectively, following the order: P-CD > P-YC > P-SD > P-YM > P-XM, with wheat straw's cumulative potassium release rate being significantly lower than the other straw types (Table 8).

3. Discussion

3.1 Effects of Different Land Use Patterns on Decomposition Characteristics of Different Straw Types

Numerous factors influence crop straw decomposition rates and average decomposition amounts at various stages, including straw properties, tillage methods, burial depth, soil physicochemical properties, and climate. The straw decomposition process primarily depends on microbial decomposition. Among the many influencing factors, some are direct factors, while others indirectly affect the decomposition process by influencing microbial activities. Previous studies have shown that the decomposition process of crop straw in soil is typically divided into two stages: rapid decomposition and slow decomposition. The rapid de-

composition stage refers to the early period when the decomposition of soluble organic compounds and similar substances in crop straw causes a substantial reduction in straw mass. The slow decomposition stage, relative to the rapid stage, occurs in the later experimental period, during which lignin, tannin, wax, and other substances not decomposed or incompletely decomposed in the first stage undergo gradual slow decomposition through physicochemical changes, often lasting one year or longer [20-21,29].

In this study, the decomposition rates of the five straw types showed an overall upward trend with increasing decomposition time, consistent with previous research findings [22]. Some studies have shown that straw decomposition rates increase steadily with decomposition time. However, this study observed slight decreases in straw decomposition rates over time, possibly due to inconsistencies in the size and weight of the tested straw. Smaller straw pieces have larger specific surface areas, making them more accessible to soil microorganisms and enzymes, resulting in faster decomposition rates, which aligns with Hassink's [30] research findings. In dryland soil, wheat and rice straw decomposition rates showed rapid decomposition in the early stage (0-60 d) and stabilization in the later stage (60-360 d). In paddy field soil, wheat, rice, maize, and rapeseed straw reached decomposition stability after 60 d, while broad bean straw stabilized after 90 d. This was mainly because during the first 60 d of the experiment (June-August), temperatures were high, especially ground temperatures, resulting in higher soil temperatures and stronger microbial activity. Additionally, rainfall was abundant during this period, promoting rapid straw decomposition. After September, temperatures gradually decreased, soil temperature dropped, and microbial activity weakened substantially, slowing straw decomposition. During the overwintering period, straw decomposition nearly ceased. Although temperatures recovered in March and April of the following year, easily decomposable substances such as proteins, water-soluble compounds, and hemicellulose in the straw were nearly exhausted, leaving behind recalcitrant substances like lignin and cellulose that prevented further increases in decomposition rates. Additionally, in both paddy field and dryland environments, maize straw decomposition rates during the rapid decomposition period were significantly lower than those of the other four straw types, which differs from previous research conclusions [23,31]. Since straw C/N ratio also affects decomposition rates [31], and the C/N ratio of maize straw in this experiment was higher than that of rice, rapeseed, and broad bean straw, further research is needed to explain the differences with wheat straw decomposition rates.

Comparing dryland and paddy field environments, decomposition rates of all five straw types were higher in dryland than in paddy field. Dryland soil is in an aerobic state, while paddy field soil is in an anaerobic state. Wang et al. [32] found that the residual amounts of cellulose, hemicellulose, and lignin in wheat straw generally decreased with incubation time, and that aerobic conditions were more conducive to the degradation of cellulose, hemicellulose, and lignin. Therefore, dryland environments are more favorable for crop straw decomposition than paddy field environments.

3.2 Effects of Different Land Use Patterns on Nutrient Release Characteristics of Different Straw Types

After straw return, decomposition occurs through the action of soil microorganisms, releasing nitrogen, phosphorus, potassium, and micronutrients for crop uptake [33]. Therefore, straw return is widely recognized as an effective measure for improving soil physicochemical properties and enhancing soil fertility. Some studies have found that leguminous green manure exhibits explosive nutrient release during the early decomposition stage (1 month) in soil [34-35], which is similar to the results obtained in this study. The rapid release stages for carbon, nitrogen, phosphorus, and potassium from straw decomposition in dryland environment were 0-90 d, 0-30 d, 0-60 d, and 0-30 d, respectively, while in paddy field environment they were 0-60 d, 0-30 d, 0-60 d, and 0-30 d, respectively. In this study, the release of carbon, nitrogen, phosphorus, and potassium from straw generally showed an increasing trend with decomposition time and tended to stabilize, consistent with previous research [15]. However, decreases in carbon and nitrogen nutrient release rates were also observed with increasing decomposition time, possibly because fertilizer (urea) application during this stage provided abundant carbon sources and nutrients for microorganisms, reducing their demand for nutrients from straw [36] and leading to decreased nutrient release rates.

Previous research has suggested that the nutrient release rate from decomposed returned straw follows the order: potassium > phosphorus > nitrogen > carbon [15,23], which is consistent with the results of this study. The form of nutrient elements in straw is the key factor determining their release speed. Potassium exists in straw in high concentrations and mostly in ionic form. Approximately 60% of phosphorus exists in ionic form, with the remainder participating in cell wall structure, resulting in slower release rates than potassium, and straw contains less phosphorus than potassium. Carbon and nitrogen in straw exist primarily in organic forms as major structural components with high degrees of cementation, making them difficult to decompose under physical action and thus releasing more slowly [22,37]. At the end of the experiment, phosphorus showed the highest release among the elements in crop straw, followed by potassium, while carbon and nitrogen showed relatively lower release.

Wang et al. [32] found that aerobic conditions were more conducive to carbon and nitrogen release from wheat straw than anaerobic conditions because anaerobic conditions inhibit the activity of aerobic microorganisms in soil and reduce microbial respiration intensity, resulting in lower straw nutrient release rates. Comparing the final release amounts of carbon, nitrogen, phosphorus, and potassium in dryland and paddy field environments in this study yields similar conclusions.

In this experiment, different straw types (wheat straw, rice straw, maize straw, rapeseed green stalk, and broad bean green stalk) showed different decomposition rates in dryland and paddy field. The rapid decomposition period occurred

30–60 d after burial. At the end of the experiment, all five straw types showed substantial cumulative decomposition (exceeding 50%). In dryland, cumulative decomposition rates followed the order: rapeseed > rice > maize > wheat > broad bean, while in paddy field the order was: rice > maize > wheat > rapeseed > broad bean, with cumulative decomposition rates in dryland being higher than those in paddy field for all straw types.

Different straw types showed rapid phosphorus and potassium release in the early decomposition stage, exceeding 90%. The nutrient release rate in both dryland and paddy field followed the order: potassium > phosphorus > nitrogen > carbon, with cumulative release rates being higher in dryland than in paddy field.

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