


## Article

# Oxidative Degradation Characteristics of Low-Temperature Pyrolysis Biochar and the Synergistic Effect on Released Nutrients

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**Abstract:** Biochar application has received much attention because biochar can be used as an organic amendment. The nutrient release patterns and interactions in straw biochar produced at different temperatures are not well understood. In this study, we observed the release patterns of carbon (C), nitrogen (N), phosphorus (P), and potassium (K) and the interaction between released C, N, P, and K from straw biochar prepared from 225 to 600 °C through a 180-day degradation experiment. The results showed that the degradation rate of the two kinds of straw biochar was faster in the first 30 days at different temperatures, and that of the straw biochar prepared before 300 °C was more rapid, indicating that 300 °C is an important turning point. The rule of nutrient release in the straw biochar showed that the K release rate was the highest and most rapid and was more than 60% in the first 30 days. The nutrient release rates for the two kinds of straw biochar were in the order  $K > N > P > C$ . The release of nutrients accompanied the decomposition of the straw biochar, and there was an exponential relationship between the amount of nutrients released from straw biochar and its degradation mass. There were collaborative or similar release processes indicated by significant positive correlations between the released C and N ( $R^2 = 0.96$ ) and P and K ( $R^2 = 0.94$ ) in the tobacco straw biochar and an obvious correlation between the released C and N ( $R^2 = 0.76$ ) in the rice straw biochar. These results indicated that the released C and N, P, and K in tobacco straw biochar, as well as C and N in rice straw biochar, have synergistic effects and the same degradation path. The application of straw biochar can provide a source of P and N in the short term and a source of P and C in the long term. This study suggests that returning straw biochar to the soil could appropriately reduce the input of K fertilizer in the early stage.

**Keywords:** pyrolysis temperature; straw biochar decomposition; nutrient release; interaction



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## 1. Introduction

Globally, agriculture produces significant amounts of waste, with straw being the most abundant. According to statistics, the total global straw production is approximately 6 billion tons [1], which is a very significant amount with enormous potential for resource utilization [2,3]. The annual crop straw production is approximately 1 billion tons in China [4]. To solve the problem of straw utilization, there have been many policies introduced to promote the formation of fertilizer, fuel, feed, raw material, and base material

utilization pathways in China [5]. Among them, straw resources are mainly used in fertilizer in China, with a utilization rate of 53.93% [6]. Consequently, there is increasing concern about the social and environmental advantages of straw fertilization and utilization.

Straw, a rich renewable resource, helps meet economic demands by conserving scarce resources, replacing depleted ones, and providing a foundation for the sustainable development of the environment in China [7]. In fact, the excessive removal of straw can cause nutrient loss in farmland and a decrease in soil nutrient content, thereby reducing the long-term production capacity of soil resources and affecting the C cycle [8]. Therefore, it is necessary to encourage innovation so that recycled straw can be applied to the soil while reducing environmental pressure. Converting straw into biochar and returning it to the field, fully realizing its potential, is expected to replace some fertilizers. For example, combining straw biochar with intelligent fertilizers can create a potential slow-release fertilizer [9], resulting in considerable added value for crop growers and involving them in the development of new products [10]. Straw biochar is a potential material for manufacturing such smart fertilizers, as it can slowly release nutrients to meet the long-term needs of plants and save costs by reducing labor [11].

Straw biochar is a solid substance produced through the high-temperature pyrolysis of crops, which has high application value in agricultural C sequestration, emission reduction, and soil improvement. The carbonization of straw into straw biochar can be used as a soil amendment to improve soil characteristics and increase agricultural productivity [12,13]. For example, when rice straw is granulated with plant silica, diatomaceous earth, and bentonite in a certain proportion and made into biochar, it has the potential to simultaneously release P and K, serving as a slow-release carrier [11]. Researchers have compared straw and straw biochar treatment in their return to the field and found that straw biochar has more potential for C fixation and can also improve the utilization efficiency of N [14]. The authors in [15] suggested that the addition of biochar can increase bacterial abundance, thereby maintaining the storage of the soil organic C pool and facilitating its long-term storage.

According to reports, straw biochar has a rich pore structure, and adding it to soil can capture free and unstable substances in the soil, which are slowly released with the leaching of water when needed for crop growth [16,17]. This is also an important reason why straw biochar could retain nutrients. Straw biochar contains a large amount of nutrients, such as N, P, and K, and when it decomposes, these nutrients can be released and provided to crops to reduce fertilizer input [18]. However, people rarely pay attention to the release patterns of nutrients from straw biochar in soil and the interactions between various nutrients during the release process. Most research into the current application of straw biochar in returning farmland only focuses on straw biochar as a “carrier” for slow-release fertilizers, a “storage reservoir” for nutrients, and a “modifier” for improving the soil environment [19–21]. However, the role of the nutrients contained in the straw biochar during the utilization process has been overlooked. Exploring the actual nutrient release patterns and intrinsic relationships between straw biochar nutrients in the field is beneficial for fully utilizing the potential of straw biochar resources in reducing fertilizer use.

Due to the uncertainty of nutrient release during the straw biochar degradation process, potential environmental risks and ecological health impacts during its use are still unknown. Specifically, the rice straw contained 36.60~50.36% C, 0.38~1.01% N, 0.08~0.45% P, and 0.23~2.45% K, and the tobacco straw contained 17.94~44.73% C, 1.04~2.30% N, 0.05~0.19% P, and 0.24~3.32% K [22]. The nutrient composition of different feedstocks imparts biochar different properties, and, therefore, they can be used exclusively for agricultural purposes. The properties of straw biochar vary due to the influence of different pyrolysis temperatures. For example, with increasing pyrolysis temperature, one typically finds increasing the C, P, K, calcium, ash content, pH, and specific surface area of biochar. In contrast, the N content seems unaffected by temperature. These biochar properties are driven by the formation of C in a more recalcitrant form; the production of carbonate mineral phases (such as P and K), leading to higher ash content and higher pH; and the loss of H and O through volatilization [23]. Thus, exploring the nutrient release patterns and intrinsic correlations

between straw biochar produced via pyrolysis at different temperatures in the soil can better tap into its potential as a fertilizer. Therefore, this study used tobacco stems and rice straw as raw materials to prepare straw biochar in the temperature range of 225–600 °C and conducted a 180-day degradation experiment. The main research objectives were as follows: (1) to explore the release law of C, N, P, and K in straw biochar; (2) to reveal the relationship between the released C, N, P, and K and degradation mass; and (3) to clarify the relationship between the intrinsic nutrients in the degradation process of straw biochar.

## 2. Materials and Methods

### 2.1. Study Site Description

The experiment was conducted from 17 May to 17 November 2023 at the experimental base of Hunan Agricultural University, with geographic coordinates of 28°17′–28°18′ N, 113°05′–113°08′ E. The experimental area belongs to a subtropical monsoon climate, with an average annual temperature and rainfall of 17.2 °C and 1361.6 mm. The tested soil is annual loam soil, with surface organic C, total N, total P, and total K contents of 17.89 g·kg<sup>-1</sup>, 1.43 g·kg<sup>-1</sup>, 0.92 g·kg<sup>-1</sup>, and 14.27 g·kg<sup>-1</sup>, respectively.

### 2.2. Straw Biochar Production

Both tobacco and rice straw were collected from the experimental fields of Hunan Agricultural University, Changsha, Hunan, China (the same variety and experimental field). The collected straw was cleaned and dried, then cut into small sections of about 5 cm and dried in an oven (60 °C). Finally, it was crushed using a hammer pulverizer (KFJ-20, Zhejiang Ruihao Machinery Manufacturing Co., Ltd., Wenzhou, China) and passed through a 1 mm sieve before being stored for future use. The properties of tobacco and rice straw biochar are shown in Table S1.

According to the preliminary experiment, it was found that the weight loss of two types of straw was significant within the range of 200–600 °C, with a sharp decrease between 225 and 300 °C and the maximum at 300 °C. After 600 °C, it slowed down and gradually stabilized. Therefore, pyrolysis was conducted at intervals of 15 °C between 225 and 300 °C and multiples of 50 °C between 300 and 600 °C.

The pyrolysis experiment was conducted in a box-type, high-temperature sintering furnace (KSL-1700X, Hefei Kejing Materials Technology Co. Ltd., Hefei, China) with approximately 60 g of sample weighed each time and placed in a customized sealed tank at a heating rate of 10 °C·min<sup>-1</sup> for 1 h at 225, 240, 255, 270, 285, 300, 350, 400, 450, 500, 550, and 600 °C, respectively. The pyrolysis experiment was repeated three times for each type of straw at different temperatures, and the obtained samples were stored for future use.

### 2.3. Experimental Setup

The decomposition and nutrient release patterns of two types of straw biochar under different temperature conditions were studied using the nylon mesh bag method under field conditions for 180 days. The nylon mesh bag had a length and width of 5 cm, respectively, and its aperture was 300 mesh. The specific operation method was to weigh 5.00 g of each sample and put it into a nylon sandbag, tighten the sealing rope to seal it, and repeat the process 18 times for each sample. As shown in Figure 1, each nylon mesh bag was randomly buried in the divided plot, the depth of the nylon sandbag was about 5 to 10 cm, and its location was marked within the plot. There was no overlap between the mesh bags, and every third sample from the same processing was arranged in the horizontal direction. Three nylon sandbags were taken out on the 30th, 60th, 90th, 120th, 150th, and 180th day of degradation, the surface soil was rinsed thoroughly, and the samples were dried in an oven to a constant weight. The remaining straw biochar was weighed and recorded. Then, the sample was stored in a self-sealing bag for subsequent nutrient content determination.

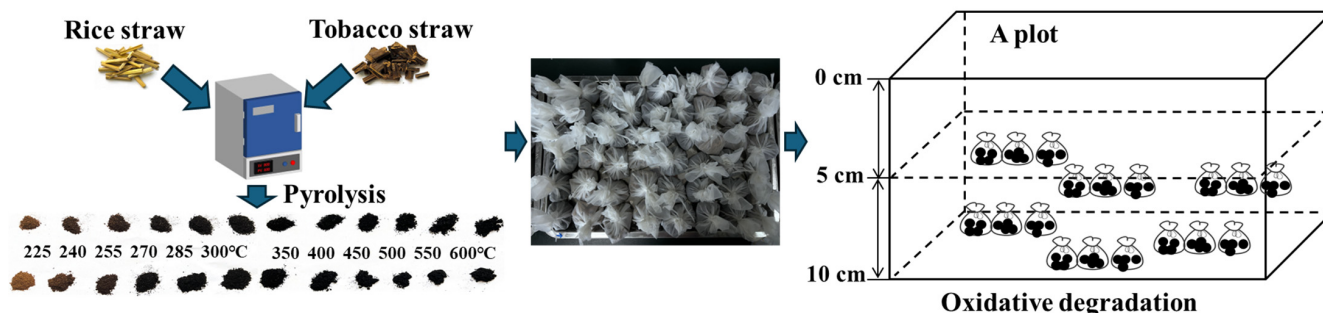


Figure 1. Biochar preparation and degradation process.

#### 2.4. Indicator Measurement Method

The potassium dichromate sulfuric acid external heating method determined the C content in the straw biochar. Specifically, 0.1000 g of the sample was weighed in a digestion tube, and 5 mL of potassium dichromate solution with a concentration of  $0.80 \text{ mol}\cdot\text{L}^{-1}$  and 5 mL of concentrated sulfuric acid were added. The sample was heated to boiling at  $240^\circ \text{C}$  and maintained for 5 min. After cooling, the sample was titrated with  $0.2 \text{ mol}\cdot\text{L}^{-1}$  ferrous sulfate solution and the endpoint was titrated using an ortho phenanthroline indicator. The straw biochar was digested with sulfuric acid–hydrogen peroxide at high temperatures to obtain a milky white solution. The solution was filtered and divided into three parts after cooling for the determination of N, P, and K, respectively. The N content was determined using a Kjeldahl nitrogen analyzer (KN680, Jinan Alva Instrument Co., Ltd., Jinan, China), the P content was measured using the colorimetric method with ammonium molybdate, and the K content was determined via ICP-MS (PerkinElmer 8300, Perkinelmer Enterprise Management (Shanghai) Co., Ltd., Shanghai, China). All experiments were conducted in triplicate.

#### 2.5. Statistical Analysis

The degradation rate and nutrient release rate of the straw biochar were calculated using Formulas (1) and (2), respectively:

$$\text{Straw biochar decomposition rate (\%)} = (M_0 - M_x)/M_0 \times 100\% \quad (1)$$

$$\text{Nutrient release rate (\%)} = (N_0 - N_x)/N_0 \times 100\% \quad (2)$$

where  $M_0$  is the mass of the straw biochar before the experiment, 5 g;  $M_x$  is the mass of the straw biochar at the  $x$ -th sampling, g;  $N_0$  represents the nutrient quality of the straw biochar before the experiment, g; and  $N_x$  represents the nutrient quality of the straw biochar during the  $x$ -th sampling, g.

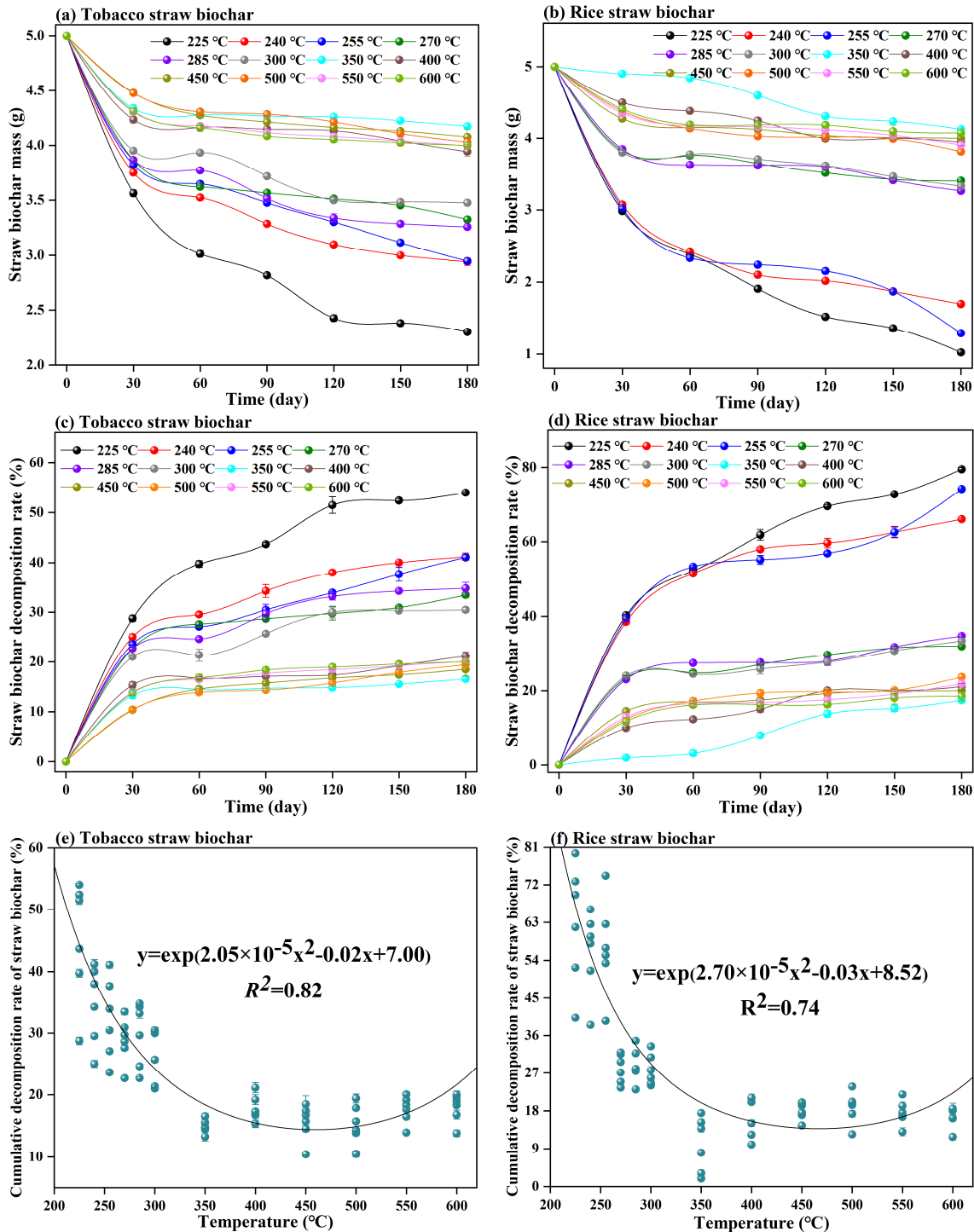
All the data were organized using Excel 2021 and plotted, and unitary regression analysis was conducted using Origin 2021. The correlation coefficient ( $R^2$ ) was selected to evaluate the goodness of fit.

### 3. Results and Discussion

#### 3.1. Changes in Straw Biochar Mass under Different Temperatures

Figure 2 shows the dynamic changes in the biochar masses and degradation rates of two kinds of straw over time. The results showed that the degradation rate of straw biochar decreased with an increase in the carbonization temperature, and the mass of straw biochar decreased with an increase in the decomposition rate over time. The degradation of the straw biochar mainly occurred in the first 30 days, and the subsequent degradation rate gradually slowed down. In addition, the degradation rate of straw biochar prepared before  $300^\circ \text{C}$  was relatively faster than that prepared at  $300^\circ \text{C}$ , indicating that  $300^\circ \text{C}$  is an important turning point for the stability change of straw biochar. The mass of tobacco straw biochar prepared before  $300^\circ \text{C}$  and after  $300^\circ \text{C}$  decreased by 1.52–2.70 g and 0.83–1.06 g, respectively, after

180 days, and the decomposition rate reached 30.47~54.00% and 16.53~21.13%, respectively. Similarly, the mass of rice straw biochar prepared before 300 °C and after 300 °C decreased by 1.60~3.98 g and 0.87~1.19 g, respectively, after 180 days, while the decomposition rate reached 31.93~79.53% and 17.47~23.73%, respectively.



**Figure 2.** Dynamics of straw biochar mass (a,b) and decomposition rate (c,d) under different temperatures. Numerical relationship between pyrolysis temperature and cumulative decomposition rate of straw biochar (e,f).

The results showed that the biochar prepared before 300 °C was more easily degraded, and the degradation effect of rice straw biochar was better. The change in the pyrolysis

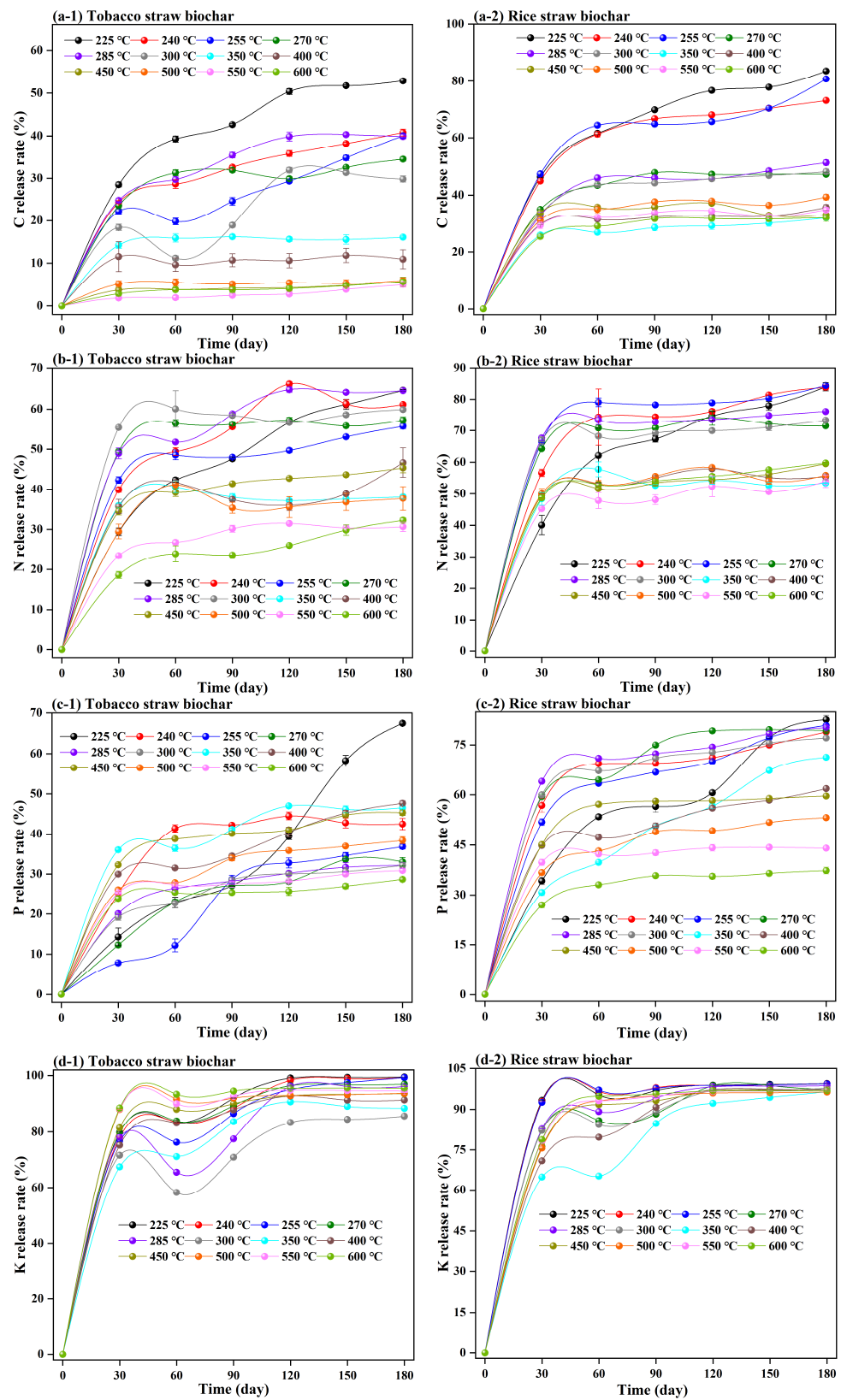
temperature affected the change in the characteristics of straw biochar [24]. The unstable substances in straw biochar generated by low-temperature pyrolysis, such as hydrogen, oxygen, and K, were not completely lost, and these unstable substances were more easily decomposed under anaerobic soil conditions [25]. In addition, the straw biochar produced before 300 °C still existed in the cellulose and hemicellulose. The cellulose and hemicellulose, the main components of straw [26], served as nutritional sources for soil microbes. With increasing microbial metabolic activity, the decomposition of straw biochar also accelerated [27]. The straw biochar prepared after 300 °C formed a more stable aromatic structure, which was not easily decomposed in the soil but could be used as a habitat for microorganisms. In addition, there was a strong exponential relationship between the decomposition rate of the two types of biochar and the pyrolysis temperature ( $R^2 = 0.82$  and  $R^2 = 0.74$ ; Figure 2e,f), indicating that pyrolysis temperature is an important factor affecting biochar degradation.

### 3.2. C, N, P, and K Release from Straw Biochar Decomposition

Figure 3 shows the dynamic changes in the C, N, P, and K in straw biochar during decomposition. The results show that the nutrient composition changed sharply in the first 30 days and then tended to be stable, especially the release of K from straw biochar, which was more rapid. From the decomposition rate of straw biochar, the release rate of K was the fastest, and the release rate of P and C was relatively slow. The basic performance of nutrient elements in the two kinds of straw biochar was  $K > N > P > C$ , indicating that straw biochar could be used as a source of K and N in the short term and a source of P and C in the long term. However, the total amounts of C, N, P, and K nutrient elements released from each straw biochar type were in the order of  $C > K > N > P$ , and the amount of rice straw biochar was higher. This is because the straw biochar was mainly composed of a C skeleton; thus, its C content was also high. In addition, at the same pyrolysis temperature, the C content of rice straw biochar was significantly higher than that of tobacco straw biochar (Table S2), and the unstable C component was easily released. Furthermore, the nutrient release from the straw biochar produced before 300 °C was faster, while that produced after 300 °C was slower, indicating that straw biochar produced after 300 °C is more conducive to achieving synchronous adaptation to crop nutrient absorption patterns.

According to the rate of C release from the straw biochar (Figure 3(a-1,a-2)), the release of C at different temperatures can be divided into the fast-release period (0~30 days) and the slow-release period (30~180 days), especially for straw biochar produced after 300 °C. Throughout the whole degradation period, the cumulative C release rate of tobacco straw biochar was 5.02~52.86%, while the release from rice straw biochar was 32.03~83.55%, indicating that rice straw biochar is easier to decompose, mainly because of the difference in C contents and the structures of the two kinds of straw biochar (Table S2). The lower the pyrolysis temperature, the greater the amount of C that was released from the straw biochar. Tobacco straw is mainly composed of plant cell walls, and the decomposition rate of its components is generally hemicellulose, cellulose, and lignin in turn; of course, there is also a small amount of easily decomposed proteins and water-soluble substances [28]. Due to the covalent binding of hemicellulose and lignin in the straw and the cellulose being wrapped by hemicellulose and lignin [29], during the pyrolysis process, it is difficult for hemicellulose, cellulose, and lignin to be completely degraded. It is also easier to form a stable C structure, so the nutrients are not easily released. With an increase in temperature, the hemicellulose and cellulose in straw undergo dehydration, decarboxylation, and decarbonylation reactions [30], and the remaining structure is rearranged to form a more stable aromatization structure; thus, less C is released. The application of biochar improved the C cycle of soil and the photosynthesis process of crops, affecting the carbohydrate synthesis and dry matter distribution process [31]. For example, Nan et al. found that the application of biochar promoted the uptake and utilization of CO<sub>2</sub> and dry matter accumulation by crops by altering the C cycle process [32]. In addition, biochar contains organic C that can be absorbed by crops, which is conducive to the improvement of their own yield after

absorption and utilization [33]. Therefore, the release of C from biochar is essential for the growth of crops.



**Figure 3.** Characteristics of C (a-1,a-2), N (b-1,b-2), P (c-1,c-2), and K (d-1,d-2) release rate of tobacco straw biochar and rice straw biochar for different temperatures.

The N release law of the straw biochar under different temperature treatments is shown in Figure 3(b-1,b-2). Except for the treatment at 225 °C, the release of N in the two kinds of straw biochar was similar to that of C, with rapid release in 0~30 days, a relative slowdown in 30~60 days, and stable release after 60 days. Overall, the higher the preparation temperature, the lower the N release rate of straw biochar. This is mainly because ammonium N is removed during pyrolysis [34], especially at higher temperatures. Unstable ammonium N is more likely to be lost in the form of volatile distribution, resulting in less N observed from the solid structure. At the same time, the unreleased parts of the straw biochar will recombine, making it more difficult to open the interior of the biochar and release N. This also explains the phenomenon that more N was released from the straw biochar produced before 300 °C than from that prepared after 300 °C. As shown in Figure 3(b-1,b-2), the cumulative release rates of N from tobacco straw biochar and rice straw biochar prepared before 300 °C were 55.74~64.61% and 71.48~84.47%, respectively, while those from tobacco and rice straw biochar prepared after 300 °C was 30.65~46.65% and 53.40~59.74%, respectively. Similarly, the release of N from the rice straw biochar was significantly higher than that from tobacco straw biochar, which was due to the difference in N content in the two kinds of straw biochar (Table S2). In addition, large amounts of C and N were released from the straw biochar prepared before 300 °C in the early stage of cultivation, leading to excessive accumulation, which may have regulated the balance of C and N content in the soil and inhibited the utilization of C by microorganisms in the soil. The release of C and N in straw biochar produced after 300 °C was relatively slow, and the stimulating effect on C and N in the soil was relatively weak. Therefore, straw biochar prepared after 300 °C may be more conducive to its use as a fertilizer.

As seen in Figure 3(c-1,c-2), there was a difference in P release between the two types of straw biochar. Except for the biochar prepared at 225 °C, the release of P from tobacco straw biochar was slow in the first 60 days and stable after 60 days. The P in rice straw biochar could be divided into a rapid release stage (0~30 days) and a stable release stage (30~180 days). The P release rate in the tobacco straw biochar at 225 °C reached 67.47%, while the rates for types of biochar at other temperatures were 28.69~42.67% and 37.33~82.66%, respectively. In addition, the release of C and N was lower before 300 °C, and more P was released from the straw biochar prepared after 300 °C. The release of P from straw biochar generally showed a trend of slowly increasing and then gradually decreasing with increasing temperature. The P in straw mainly existed in the form of insoluble organic matter [35], while the rest existed in the form of ions. After pyrolysis, the insoluble organic P in the straw gradually dissolved, leading to the gradual release of P. As the temperature increased, a P mineral crystal structure gradually formed in straw biochar, making it difficult to release into the soil.

Figure 3(d-1,d-2) shows the release pattern of K in straw biochar. The release of K in the two types of straw biochar showed two stages: rapid release (0~30 days) and slow release (30~180 days), with a slight decrease on the 60th day and a gradual slow release after 60 days. The K release rates of two types of straw biochar were as high as 85.67% to 99.97% and 96.48% to 99.47% in the first 30 days, indicating that the K in the straw biochar had been released. By the end of cultivation, the K had been completely released, further indicating that straw biochar could be used as a source of K in the early stage of crop growth. In addition, the K in straw biochar mainly existed in the form of ions and was easily soluble in water [23,36]; therefore, the release rate of K was the fastest. In addition, the K content in straw biochar was relatively high, resulting in more release. As the temperature increased, the cumulative release rate of K also gradually increased. This is because the K content in straw biochar was positively correlated with the pyrolysis temperature [37]. The higher the temperature, the higher the K content, leading to an increase in the amount released.

### 3.3. Relationship between Straw Biochar Decomposition Mass and Released Nutrients

Figure 4 shows the relationship between the released C, N, P, and K and the decomposition mass of straw biochar prepared at different pyrolysis temperatures. It can be seen in Figure 4 that the released C, N, P, and K increased exponentially with the increasing decomposition mass of straw biochar. This further indicated that the degradation of the straw biochar was accompanied by the release of nutrients, but there were differences between different types of straw biochar. Straw biochar can provide abundant C and nutrient sources for microorganisms, thereby increasing their quantity and enhancing their activity. However, the nutrient release of straw biochar produced at different temperatures varies due to its complex structure. Additionally, the release of C from the rice straw biochar was significantly higher than that from the tobacco straw biochar, while there was no significant difference in the release of other nutrients, indicating that the C in the tobacco straw biochar was more stable than that in the rice straw biochar.

The release of C from the two types of straw biochar was exponentially correlated with the degradation quality of straw biochar ( $R^2 = 0.86$  and  $R^2 = 0.78$ ; Figure 4(a-1,a-2)), indicating that the released C exponentially decreased from the straw biochar as the decomposition mass of straw biochar decreased. This is because the unstable C components in straw biochar were progressively released over time. In addition, as the temperature increased, the hemicellulose and cellulose in the straw biochar gradually underwent dehydration, decarboxylation, and decarboxylation reactions [24], forming a more stable aromatic structure and making it less likely for C to be released. In addition, the release of C from straw biochar was mainly concentrated in its early degradation stage, especially in rice straw biochar. The higher the degradation, the more C was released. As seen in Figure 4(b-2), the released N from the rice straw biochar had a significant exponential function relationship with its degradation ( $R^2 = 0.98$ ), indicating that N was more easily released from the rice straw biochar. Similarly, the released P exponentially decreased as the decomposition mass from tobacco straw biochar (Figure 4(c-1);  $R^2 = 0.80$ ). However, the exponential relationship between released N and decomposition mass was not strong from tobacco straw biochar produced at different pyrolysis temperatures. Also, the released P from rice straw biochar and the released K from tobacco and rice straw biochar showed a weak exponential relationship with decomposition mass. The released C, N, P, and K in the straw biochar and decomposition mass represent exponential decay models. The N, P, and K were gradually released in the early stages of straw degradation, with less being released in the later stages. This is because the unstable part of straw biochar was preferentially decomposed by microorganisms in the soil [38]. In addition, the degradation of straw biochar was accompanied by the release of its nutrients, indicating a certain relationship between the various nutrients in straw biochar. The interrelationships between nutrients will further affect the decomposition process of straw, thus, it is necessary to further analyze the relationships between the various nutrients released from straw biochar.

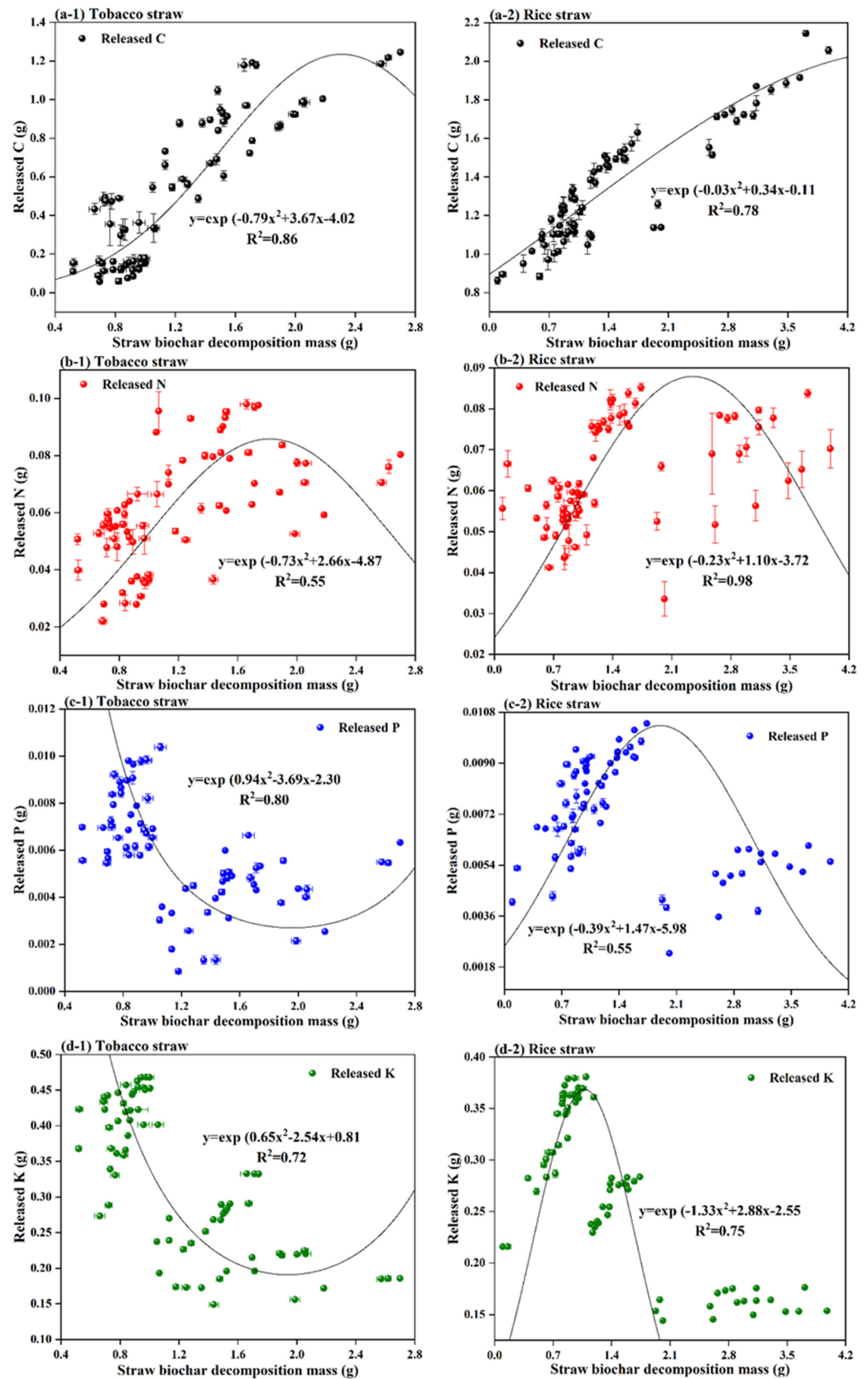
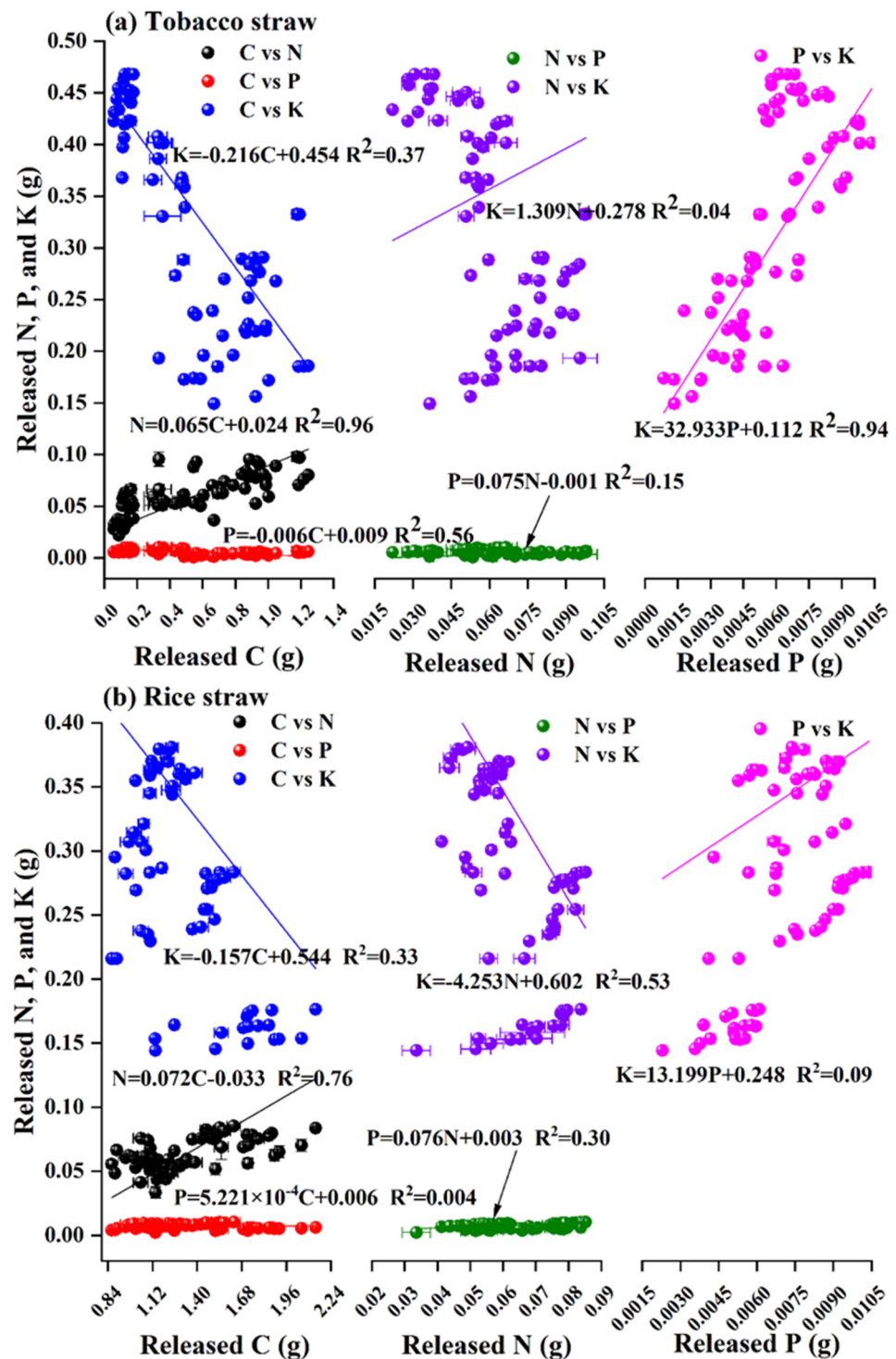


Figure 4. Numerical relationship between straw biochar decomposition mass and released C (a-1,a-2), N (b-1,b-2), P (c-1,c-2), and K (d-1,d-2).

### 3.4. Interaction between Released C, N, P, and K from Straw Biochar

In addition to the effect of different pyrolysis temperatures on the release of nutrients from straw biochar, the C, N, P, and K released during the degradation process also affected each other. The correlation analysis between the released C and N and P and K from tobacco straw biochar and rice straw biochar is shown in Figure 5a,b. For tobacco straw biochar (Figure 5a), there was a significant positive linear correlation between the released C and N ( $R^2 = 0.96$ ) and P and K ( $R^2 = 0.94$ ) from tobacco straw biochar, indicating that the C and N and P and K in tobacco straw biochar shared the same pathway during the release process. There was also a synergistic effect between C and N, P, and K. Previous studies have also shown that the input of straw or straw biochar can regulate the C/N ratio of the soil [27], thereby affecting C and N cycling. Generally, the appropriate C/N ratio in the soil is suitable for the growth of microorganisms [39], while in this study, the C and N in the straw biochar were released synchronously, indicating that the metabolism of the microorganisms in the soil was not limited by C or N. The release of P and K from the straw biochar was also positively correlated, indicating that their degradation was uniform before 180 days; these research results were similar to those of [11]. In addition, there was a negative correlation between C, P, and K, indicating that the released C from the straw biochar was limited by P and K. The degradation of C occurred throughout the entire cultivation period, while the release of P and K was relatively fast. This further indicated that the application of straw biochar could serve as a beneficial source of P and K to soil microorganisms in the short term and as a source of C and N in the long term. Of course, the nutrient elements in biochar are limited, and some fertilizers need to be added appropriately to provide nutrients in the process of crop planting. The interaction between the N, P, and K released from the straw biochar was not significant, indicating that these nutrients were less affected by each other. For the rice straw biochar, except for a negative correlation between N and K, the interaction relationship between other nutrients was similar to that of tobacco straw biochar. The N in rice straw biochar was not affected by the pyrolysis temperature and seemed unaffected by different nutrients. In addition, the  $R^2$  of various nutrients released from the tobacco biochar was higher than that in rice straw biochar, which means that the nutrient release from the tobacco biochar showed a higher correlation effect.

Low-temperature pyrolysis may be an important factor in determining the intrinsic nutrient characteristics and nutrient release rate of straw biochar. Pyrolysis can transform organic matter in straw to different degrees according to different temperatures. To reduce the loss of organic matter, pyrolysis should be carried out at low temperatures. However, it should be noted that biochar produced by low-temperature pyrolysis (e.g.,  $<500\text{ }^\circ\text{C}$ ) has fewer pores, and diffusion of N, P, and K may be limited. In addition, temperatures below  $200\text{ }^\circ\text{C}$  may cause the lignocellulosic structure of the straw not to be completely carbonized, which is not conducive to the released of nutrients. However, some studies have found that the change in the silicon content of straw may make the release of nutrients more flexible and controllable [11], and the silicon content in different kinds of straw is different, thus controlling the release process of nutrients from straw biochar in soil. Therefore, future studies can focus on the regulatory mechanism of silicon conversion in straw upon nutrient release from biochar.



**Figure 5.** The cross-correlation of released C, N, P, and K from tobacco straw biochar (a) and rice straw biochar (b).

#### 4. Conclusions

This study examined the degradation behavior of straw biochar in soil at different pyrolysis temperatures. The pyrolysis temperature significantly influenced the degradation behavior of the straw biochar in the soil. The findings showed that 300 °C is an important transition temperature, as the biochar degradation rate and the nutrient release of straw prepared before 300 °C were higher, while the nutrient release of straw biochar produced after 300 °C gradually reduced. The degradation of straw biochar produced at different

pyrolysis temperatures was rapid at first and then slowed down, and the contents of C, N, P, and K were released rapidly in the first 30 days. Specifically, the K was released from the biochar the fastest, with a release rate more than 60% in the first 30 days. The release rates of nutrients in the two kinds of straw biochar were in the order of  $K > N > P > C$ . The rice straw biochar was more easily degraded than tobacco straw biochar, and there was an exponential relationship between nutrient release and degradation. In addition, correlation analysis showed that there was a significant positive correlation between the C and N released from the two kinds of straw biochar ( $R^2 = 0.96$  and  $R^2 = 0.76$ ), and there was also a significant positive correlation between the P and K released from tobacco straw biochar ( $R^2 = 0.94$ ). This study's findings suggest that the input of K fertilizer can be appropriately reduced in the early stage of straw biochar being returned to the field.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agronomy14091898/s1>, Table S1: The basic properties of tobacco straw and rice straw; Table S2: Composition of crop straw biochar under different temperatures.

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