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The dynamic changes of phosphorus availability in straw/biochar-amended soils during the rice growth revealed by a combination of chemical extraction and DGT technique

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Abstract

Purpose This study compares the dynamic effects of straw and biochar on soil acidity and phosphorus (P) availability in the rice growth period to reveal how straw and biochar affect the availability of phosphorus in soil and utilization of P for rice crop.

Materials and methods In the pot experiment, rice straw, canola stalk, and corresponding biochars were mixed uniformly with the Ultisol. Soil samples were collected at four stages of rice growth to analyze the dynamic changes of soil acidity and P availability. The availability of phosphate in straw/biochar-amended soils were evaluated using a combination of chemical extraction and diffusive gradients in thin films (DGT) technique.

Results Soil pH, KCl-P, Olsen-P, DGT-P, and Al-P deceased with the rice growth, while Fe-P increased. Biochar increased soil pH and P availability more than straw returning, especially in the mature stage, while the DGT-P only increased in the tillering stage. The DGT-induced fluxes in sediments (DIFS) model revealed that all treatments increased the capacity of soil solid phase supplementing P to pore water in the filling and mature stages. The content of total P in different rice tissues followed the order of grain > straw > root, and RB350 treatment had the highest P content in rice tissues. In the mature stage, soil pH had positive correlations with KCl-P and Olsen-P, and soil Fe-P had positive correlations with total P of root and straw.

Conclusions Application of biochar made at 550 ℃ resulted in a larger increase in available P in soil, while biochar made at 350 ℃ had more effect on the chemical forms of P. The canola stalk biochar showed a larger influence on the P availability than rice straw biochar. Biochar treatments had a larger effect on inhibiting soil acidification and improving P availability than straw returning directly.

Keywords Straw returning · Biochar · Available P · DGT-P · Inorganic P · Dynamics

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Highlight

- Soil pH and available P (KCl-P and Olsen-P) decreased with the rice growth.
- The Al-P content decreased with the rice growth, while the Fe-P increased.
- Biochar improved soil acidification and availability of P more than straw returning.
- The parameters (R, k1, k-1 and Tc) obtained by DIFS model explained the increased P availability.
- The biochar made at 350 ℃ increased the total P in the straw and grain of rice significantly.

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1 Introduction

Phosphorus (P), as the second-largest limiting element for crop growth, plays an irreplaceable role in plant growth and metabolism (Filippelli 2008). The reserves of P are declining and it is predicted that half of the known reserves will be consumed by the middle of this century, so the sustainability of P use is imminent (Gilbert 2009). Phosphate fertilizer utilization rate is usually only 10–25% in a season, which is considered to be low, resulting in a large waste of resources and serious non-point source pollution (Schoumans et al. 2015; Filippelli 2008). Therefore, researching appropriate agronomic measures to exploit accumulated P in soil is one of the important ways to achieve sustainable P utilization (Parvage et al. 2013; Manolikaki et al. 2016). At present, in addition to optimizing crop combination and tillage methods, there have been many studies on improving soil P availability by using different modifiers.

As a renewable biomass resource, straw returning can not only improve soil nutrient content but also improve soil acidification and compaction, then provide conditions for the development of organic agriculture. Meanwhile, it has been found that the crop straw had an obvious effect on improving soil P availability and cycling (Horst et al. 2001). In addition, crop straw can be used as one of the important raw materials for biochar production, which is alkaline and rich in nutrients. Studies have shown that biochar could improve soil available P content, reduce the leaching loss of P, and play an important role in improving soil structure and water-holding capacity as well as affecting the living environment of soil microorganisms to affect the P conversion in soil (Wrobel-Tobiszewska et al. 2018; Hong et al. 2018; Zhou et al. 2020). Biochar itself contained a large number of highly effective P nutrient, which could directly improve P availability, and the improvement of pH could also promote the release of fixed P in soil. Meanwhile, biochar also changed the P morphology and availability by affecting the adsorption and desorption of P (Song et al. 2018; Xu et al. 2014; Laird et al. 2010; Ulrich et al. 2018).

As the world's largest grain producer, China has a tremendous annual crop straw. The utilization of straw and its carbonized products as soil improvers is one of the important measures to achieve the utilization of biomass resources and is also a research hotspot in the renewable energy field around the world (Long et al. 2013; Venturini et al. 2019). By comparing four crop straws (canola, rice, soybean, and pea) and their biochars, Yuan et al. (2011) found that the application of straw biochar could improve pH value more than that of crop straw, which also increased with the biochar dosage. Study also found that biochar made at 300–450 ℃ could improve the bioavailability of P effectively by reducing the adsorption of P, especially in acidic soils (Eduah et al. 2019). However, Xu et al. (2016a) found that biochar interacted negatively with phosphate fertilizer in saline-sodic soil, resulting in the decrease of plant P availability of soil and crop yield. Therefore, the improvement of soil P availability by straw and biochar was not only related to the feedstock, pyrolysis temperature, and dosage but also influenced by the soil nature and crops planted (Gul and Whalen 2016; Hong and Lu 2018; Gao et al. 2019; Chen et al. 2018).

Previous studies mostly focused on the improvement effects of biochar on soil, but there were few comparative studies on the dynamic changes of straw and biochar application on soil characteristics during crop growth. Meanwhile, the diffusive gradients in thin films (DGT), as a new technique for quantifying soil available P, was used in this study to reveal the dynamic mechanism of P availability during the rice growth (Hong et al. 2018; Ding et al. 2011). This study conducted a pot experiment by applying two straws (rice straw and canola stalk) and corresponding biochars made at 350 ℃ and 550 ℃ to the Ultisol. The objectives were to (a) investigate the dynamic changes of soil acidity and P availability with the rice growth, (b) compare the effects of straw and biochar on soil acidity and P availability, and (c) explore how straw and biochar affect the uptake and utilization of P for plants. This work will provide the theoretical basis for the rational utilization of straw biomass resources and the promotion of P availability in the straw/biochar-amended soils.

2 Materials and methods

2.1 Experimental materials

The soil was sampled from 0–20 cm depth of the low hilly area in Yuyao, China (29°46′N, 121°07′E) and classified as Ultisol based on USDA Soil Taxonomy (Soil Survey Staff 2014). The soil was air-dried and passed through a 2-mm sieve. As the huge agricultural biomass resources in China, rice straw (RS) and canola stalk (CS) were taken from Yueqing City, Eastern China (28°07′N, 120°59′E) after the harvest of rice and canola in November 2017 and May 2018, respectively. The two straws were cleaned with distilled water, baked in an oven of 105 ℃ for 24 h, and passed a 2-mm sieve. The preparation process of biochar was the same as our previous study with the target pyrolysis temperatures of 350 ℃ and 550 ℃, which had better effects on soil improvement (Yang and Lu 2021, 2022). Rice straw and biochars produced at 350 ℃ and 550 ℃ were designated as RS, RB350, and RB550, while canola stalk and biochars were designated as CS, CB350, and CB550, respectively.

2.2 Experimental setup

It was a pot experiment with 6 treatments of RS, RB350, RB550, CS, CB350, and CB550. The application rate of straw was 1% and the biochar amount was calculated by the 1% of straw amount and yield of corresponding biochar. The straw/biochar and soil were mixed fully. The soil without straw/biochar was designed as the control (CK). Triplicate samples were prepared for each treatment. Three rice seedlings were transplanted into each pot. The water level in the pot was kept 2 cm high above the surface of soil throughout the growth period. The fertilization, water management, and planting practices were detailedly described in Yang and Lu (2022). Soil samples were collected by mixing 0–20 cm soils with a potted sampler at the seedling, tillering, filling, and mature stages of rice growth, respectively.

2.3 Soil, straw, biochar, and plant analyses

The routine procedures were used to measure the physicochemical properties of soil and plant (Bao 2000). The pH of soil and straw/biochar was determined using a pH electrode with a soil:water ratio of 1:2.5 and a straw/biochar:water ratio of 1:20, respectively. Total organic carbon (TOC) was measured by potassium dichromate digesting and ferrous sulfate titration method. Total phosphorus (TP) of straw, biochar, and plant were measured by H_2SO_4 digesting and molybdenum blue colorimetric method. The exchangeable acid was determined by KCl extraction and NaOH titration method. Soil available P (KCl-P and Olsen-P) was extracted by KCl and $NaHCO_3$ solutions, respectively, and the P contents were measured by the colorimetric molybdenum blue method (Murphy and Riley 1962). The elemental analyzer (Flash EA1112, Thermo Finnigan, Italy) was used to measure the elemental contents of straw, biochar, and soil, including the contents of C, H, S, and N. The O content was obtained by subtracting the contents of C, H, S, N, and ash from the total amount. The physicochemical properties of soil, straw, and biochar can be seen in Table S1.

2.4 Soil P fractions

The chemical forms of inorganic P were measured with different solubility (Hedley et al. 1982). The aluminum phosphate (Al-P) was extracted by 0.5 mol L^{-1} NH_4F with pH 8.2, iron phosphate (Fe-P) by 0.1 mol L^{-1} NaOH and 0.1 mol L^{-1} Na_2CO_3, and calcium phosphate (Ca-P) by 0.5 mol L^{-1} H_2SO_4, which fractionation procedure was operated sequentially. The contents of P in the filtrates were measured using the colorimetric molybdenum blue method (Murphy and Riley 1962).

2.5 DGT measurements and analysis

The Zr-oxide DGT device has been reported to measure the labile P, which component introduction, deployment process, and parameter calculation were described in detail elsewhere (Zhang et al. 1998; Ding et al. 2011; Hong et al. 2018). Soil samples were adjusted to the 70% of water-holding capacity and put into DGT holes for balancing 24 h. The measured DGT-P is the P concentration that is fixed in the DGT device films including soluble P in soil pore water and bound P easily released from soil solid phase, while the DET-P is the P concentration only in soil pore water (Ding et al. 2018). DGT Induced Fluxes in Sediments (DIFS) model was used to estimate the adsorption–desorption rate of P from solid phase to liquid phase by simulating the response of DGT to P release characteristics (Menezes-Blackburn et al. 2016; Harper et al. 2000). The DGT device used in our experiment was purchased from EasySensor Ltd. (www.easysensor.net).

2.6 Data analysis

The statistical analyses were the mean of three replicates with standard deviations and performed by SPSS 19.0 (SPSS, Inc., Chicago, IL, USA). One-way ANOVA (analysis of variance) was used to analyze data variance and test the treatments' significance using LSD at 0.05 level. The pheatmap-package and R package vegan were performed for clustering analysis.

3 Results

3.1 Soil pH and acidity

The dynamic changes of soil pH and exchangeable acid in the straw/biochar-amended soils are shown in Fig. 1. Both soil pH and exchangeable acid showed decreasing trends with the rice growth, especially in the early period. In the seedling stage, soil pH increased while the exchangeable acid content decreased significantly ($p < 0.05$) after the application of straw and biochar except for RB550. The highest soil pH value and the smallest exchangeable acid content appeared in soils amended by CB350, which were 6.30 and 0.78 cmol kg^{-1}, respectively. In the tillering stage, different treatments decreased soil pH except for RB550, and all treatments had no obvious effect on the exchangeable acid. In the filling and mature stages, biochar treatments improved soil acidity with higher pH and lower exchangeable acid content while straw treatments had no significant effect. In the mature stage, the pH value of RB550 and CB550 increased by 0.26 and 0.23 units, and the exchangeable acid content of RB350 and CB350 decreased by 40.9% and 49.0% compared with the control, respectively. However, there were no significant differences between the pyrolysis temperature of 350 and 550 ℃ for the same feedstock.

3.2 Available P

The dynamic changes of soil available P in the straw/biochar-amended soils are shown in Fig. 2. Both the contents of KCl-P and Olsen-P decreased with the rice growth, and the available P contents were higher under biochar than straw treatments in different rice growth periods. In the seedling stage, the content of KCl-P significantly ($p < 0.05$) increased under treatments of RS, RB350, RB550, and CB550, which increased by 74.5% and 73.1% under RB350 and RB550, respectively. The Olsen-P content increased significantly ($p < 0.05$) in the straw/biochar-amended soils except for RS treatment. In the tillering stage, the addition of biochar significantly increased the contents of KCl-P by 17.4–35.2% and Olsen-P by 6.11–39.2%, respectively. The CB550 treatment showed a better effect on the available P in the filling and mature stages,

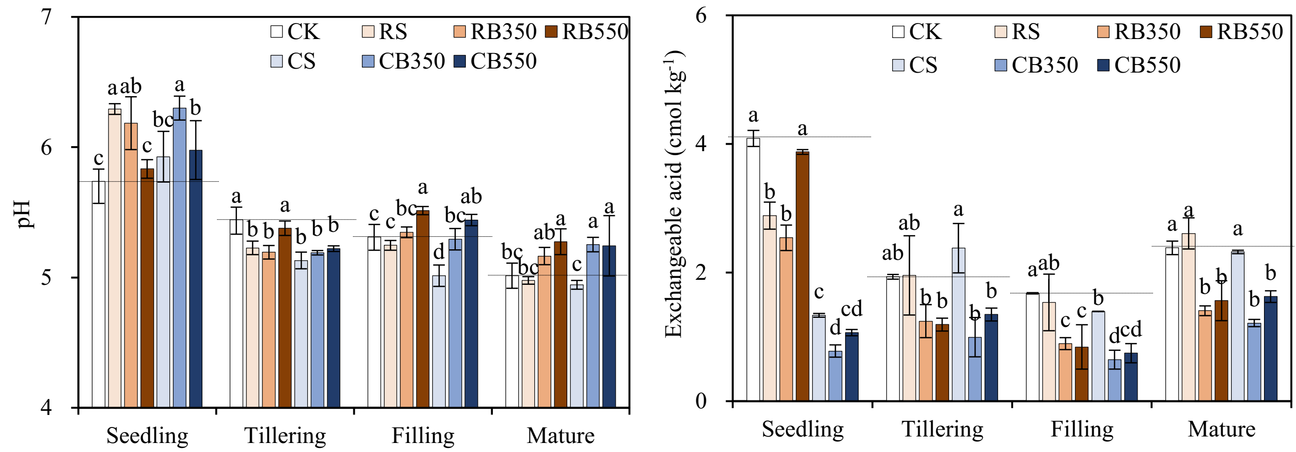

Fig. 1 Effects of straw and carbonization returning on soil pH and exchangeable acid at different stages of rice growth. Error bars represent standard error of the means ($n=3$). Different letters indicate significant differences between treatments at $p<0.05$ level

which increased by 65.4% and 124% of KCl-P, and 37.7% and 95.2% of Olsen-P, respectively, compared to the control.

3.3 Labile DGT-P concentration

Figure 3 shows the dynamic changes of soil DGT-P content in the straw/biochar-amended soils. Similar to KCl-P and Olsen-P in soils, the content of DGT-P also decreased with the rice growth, from 31.5 μg L^{-1} in the seedling stage to 20.2 μg L^{-1} in the mature stage. All treatments decreased or had no significant changes on the DGT-P except for tillering stage. In the tillering stage, biochar had more significant improvement on DGT-P than straw treatments. The content of DGP-P increased by 11.3% and 15.1% at RB550 and CB350 treatments, respectively. Table 1 shows the parameters obtained by DIFS model fitting. The R value represented the diffusion effect of P in soil pores and the supplementing P capacity of soil solid phase to pore water. Different treatments increased the R value, the adsorption (k_1), and desorption (k_{-1}) rate, while decreased the system reaction time (T_c) in the filling and mature stages. However, these parameters showed opposite changes in the seedling and tillering stages except for the K_d value. Results indicated that the straw and biochar treatments could increase the capacity of P supply to soil solution in the late growth period of rice, which could be absorbed by the plants and improve the P bioavailability in soils.

3.4 Inorganic P

The dynamic changes of soil Al-P, Fe-P, and Ca-P in the straw/biochar-amended soils are shown in Fig. 4. With the rice growth, the content of Al-P in soils decreased

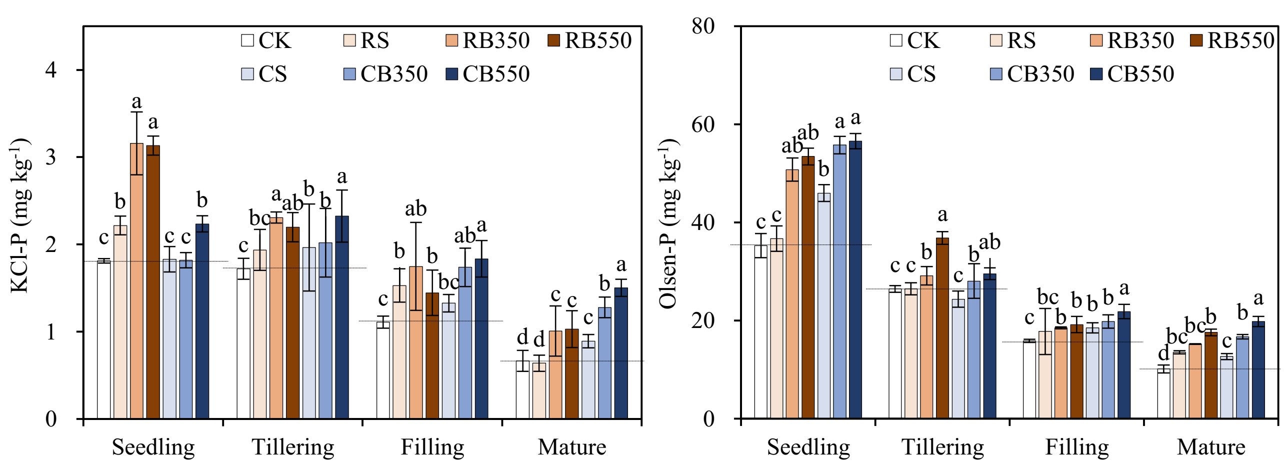

Fig. 2 Effects of straw and carbonization returning on the contents of KCl-P and Olsen-P at different stages of rice growth. Error bars represent standard error of the means ($n=3$). Different letters indicate significant differences between treatments at $p<0.05$ level

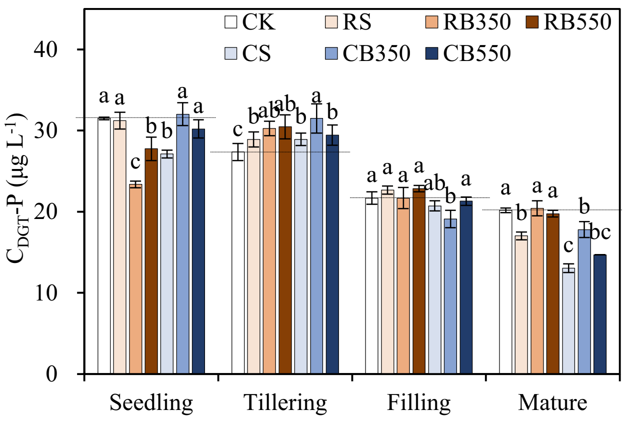

Fig. 3 Effect of straw and carbonization returning on DGT-P concentration at different stages of rice growth. Error bars represent standard error of the means ($n=3$). Different letters indicate significant differences between treatments at $p<0.05$ level

and the biochar treatments had higher content of Al-P than straw treatments. The CB550 treatment increased the content of Al-P in the seedling and tillering stages by 35.3% and 96.3%, while the RB350 treatment increased the content of Al-P in the filling and mature stages by 42.8% and 68.8%, respectively, compared to the control. The content of Fe-P showed an increasing trend with the rice growth. The RB350 and CB350 treatments in different stages of rice growth had the largest content of Fe-P except for the seedling stage. In the mature stage, all straw and biochar treatments enhanced the Fe-P content. The RB350 and CB350 treatments increased the content of Fe-P in soils by 39.1% and 26.9% relative to the control treatment, respectively. The content of Ca-P showed the trend of increasing first and then decreasing with the rice growth. Only in the filling stage, the application of straw and biochar significantly ($p<0.05$) increased the content of Ca-P by 15.6–39.9%.

3.5 Total P in different parts of rice

The effects of straw and biochar on the total P in different tissues of mature rice are shown in Fig. 5. The total P content in different tissues followed the order of the

Table 1 DIFS (DGT-induced fluxes in sediments and soils)-derived parameters reflecting P depletion from soil pore water by DGT, soil P diffusion, and kinetics of P resupply from soil solid matrix

Rice growth stage	Treatment	R	K_d	$T_c \times 10^4$ (s)	$k_1 \times 10^{-5}$ (s^{-1})	$K_{-1} \times 10^{-6}$ (s^{-1})
Seedling	CK	0.87	19.45	0.16	60.83	25.02
	RS	0.70	16.56	0.77	12.92	6.24
	RB350	0.37	16.07	4.82	2.08	1.03
	RB550	0.44	17.07	3.19	3.13	1.47
	CS	0.74	25.13	0.68	14.73	4.69
	CB350	0.88	30.67	0.19	51.47	13.42
	CB550	0.68	25.31	1.00	9.96	3.15
Tillering	CK	0.80	15.38	0.36	27.54	14.33
	RS	0.75	13.66	0.53	18.81	11.02
	RB350	0.66	12.62	0.97	10.35	6.56
	RB550	0.69	16.75	0.83	11.99	5.73
	CS	0.74	12.40	0.55	18.14	11.70
	CB350	0.78	13.90	0.40	25.14	14.47
	CB550	0.63	12.71	1.11	9.00	5.67
Filling	CK	0.45	14.31	3.07	3.26	1.82
	RS	0.74	11.63	0.51	19.65	13.52
	RB350	0.62	10.60	1.13	8.85	6.68
	RB550	0.79	13.28	0.34	29.04	17.50
	CS	0.78	13.96	0.40	25.18	14.43
	CB350	0.55	11.41	1.72	5.82	4.08
	CB550	0.58	11.90	1.47	6.81	4.58
Mature	CK	0.41	15.26	3.69	2.71	1.42
	RS	0.63	21.12	1.25	8.01	3.03
	RB350	0.61	15.07	1.30	7.72	4.10
	RB550	0.66	17.10	1.03	9.76	4.56
	CS	0.73	14.18	0.61	16.32	9.21
	CB350	0.70	13.08	0.76	13.15	8.04
	CB550	0.49	13.19	2.43	4.11	2.49

R ratio of DGT-P to DET-P (P concentration in the soil pore water), K_d ratio of Olsen-P to DGT-P, T_c the characteristic time for the sediment system to reach equilibrium after disturbance is obtained by DIFS model fitting, k_1 the adsorption rate constant, k_{-1} the desorption rate constant

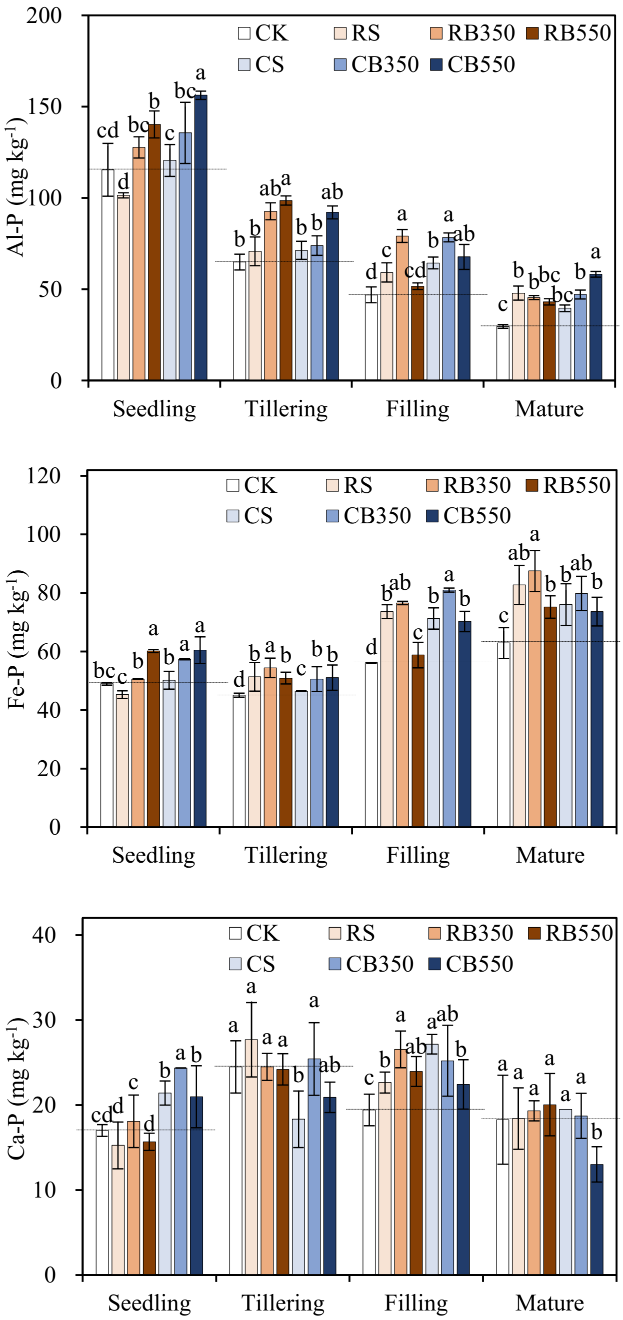

Fig. 4 Effects of straw and carbonization returning on the chemical forms of phosphorus at different stages of rice growth. Error bars represent standard error of the means ($n=3$). Different letters indicate significant differences between treatments at $p<0.05$ level

grain > straw > root. Different treatments had no obvious effect on the total P in the root except the RB350 treatment. The RB350 and CB350 treatments had the largest P content in the rice straw and grain, which increased by 203% and 149% for the straw, and 58.02% and 42.59% for the grain, respectively, compared to the control.

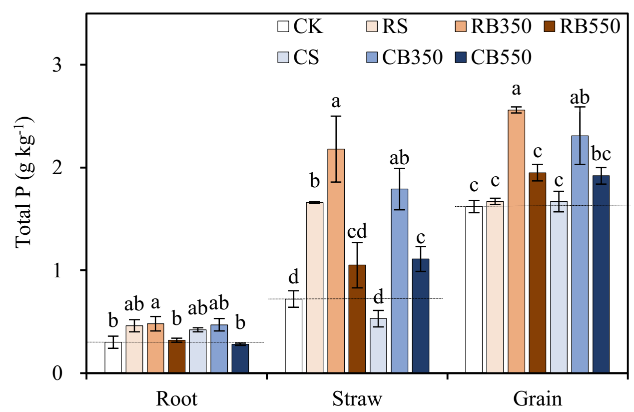

Fig. 5 Effects of straw and carbonization returning on total P content at different tissues (root, straw, and grain) of rice. Error bars represent standard error of the means ($n=3$). Different letters indicate significant differences between treatments at $p<0.05$ level

4 Discussion

4.1 Dynamic changes of soil acidity and P availability with the rice growth

Our results revealed that soil pH and the contents of available P (KCl-P, Olsen-P, and DGT-P) decreased with the rice growth. It is speculated that the two processes might cause the decrease of soil pH during rice growth. Firstly, nitrogen nitrification and salt-based ion consumption could reduce soil pH after the application of nitrogen fertilizer. Secondly, the plant root would produce excretion contained H^+ and low molecular weight organic acids (Farrell et al. 2014; Gu et al. 2017; Manolikaki et al. 2016; Bornø et al. 2018). The decreased soil available P was due to the uptake of rice growth. Meanwhile, soil pH played a vital role in affecting the availability of P (Bornø et al. 2018; Shen et al. 2016; Wrobel-Tobiszewska et al. 2018). Firstly, soil acidification could facilitate P fixation by increasing the solubility of aluminum, iron, manganese, and other metal ions and providing more active P adsorption sites. Secondly, soil pH value changed the adsorption characteristics of phosphate in soil minerals, especially the influence on phosphate of iron oxide surface (Cai et al. 2014; Guo et al. 2010). The increase of pH could improve the availability of P due to the higher solubility of phosphate (Ulrich 1986; Guo et al. 2010). Therefore, the decreased P availability was consistent with the decrease of pH value. The change of soil available P was also affected by the conversion of inorganic P (Al-P, Fe-P, and Ca-P). Results showed that the content of Al-P decreased with rice growth while the content of Fe-P increased. Thus, the change of available P with rice growth was affected jointly by Al-P and Fe-P, among which the decrease of Al-P was the main reason. Besides, the reduction of acid soil pH with the rice growth could make the precipitate of free iron and aluminum oxide dissolve, and the amount of highly active P adsorption points that iron and aluminum oxides provided increased. Although the iron phosphate was easy to hydrolyze during weathering, Fe_2O_3 film could form on the surface of the amorphous aluminum phosphate and iron phosphate, which could make it difficult to be absorbed by plants (Soinne et al. 2014). Since the Ca-P was mainly affected by the water condition, the content of Ca-P had no significant changes with the rice growth in the whole incubation process under the anaerobic conditions of flooding (Hass et al. 2012).

4.2 Comparison of soil acidity and P availability between straw and biochar returning

Results indicated that biochar treatments had a more significant effect on improving soil acidity and available P (KCl-P and Olsen-P) than straw, especially in the mature stage. Although the alkaline substances contained in straw and biochar could improve soil acidity, the alkaline functional enriched and new alkaline substances (carbonate and organic functional groups) were produced in the biochar during the pyrolysis process. Besides, the decomposition of straw in soil could accumulate acid products (Yuan and Xu 2012). Therefore, biochar returning had a more significant effect on improving soil acidification. Biochar had an important impact on the cycle of P in the soil ecosystem (Gul and Whalen 2016; Xu et al. 2016b; Wang et al. 2014; Zwetsloot et al. 2016; Manolikaki et al. 2016). There were three causes for biochar improving the availability of P: (i) the soluble P contained in biochar directly provided available P in the soil (Wrobel-Tobiszewska et al. 2018), (ii) the improved soil acidity promoted the dissolution of phosphate minerals in the soil, and (iii) the interaction between biochar and soil particles promoted the effective conversion of phosphate minerals contained in biochar. The correlation analysis also proved that there were positive correlations between soil pH and KCl-P ($R = 0.79$, $p < 0.05$), and Olsen-P ($R = 0.85$, $p < 0.05$) in the mature stage (Tables 2 and 3). DIFS model fitting confirmed that the application of biochar increased the diffusion effect of P in soil pores, the capacity of soil solid phase supplementing P to pore water and the adsorption–desorption rate of soil solid phase while reducing the reaction time T_c of soil releasing P into pore water, especially in the late growing period of rice (Harper et al. 2000; Hong et al. 2018).

The effects of biochar on different inorganic P varied greatly, which was because the change of pH, E_h, and other environmental conditions would influence the binding and release state of some metals (such as Fe and Al) with phosphate. In the mature stage, all treatments increased the contents of soil Al-P and Fe-P significantly ($p < 0.05$), but had no obvious effect on the Ca-P. The application of biochar could change the complexation between phosphate and metal ions by reducing soil acidity. On the other hand, biochar could reduce the adsorption or precipitation of phosphate in the soil by absorbing Al^{3+}, Fe^{3+}, and Ca^{2+} directly. Meanwhile, the organic molecules on the surface of biochar could effectively reduce the chelation ability of phosphate with Al^{3+}, Fe^{3+}, and Ca^{2+}. The content of available P for plants improved by the dissolve of phosphate absorbed by Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+} after the biochar application in acidic soil. Meanwhile, biochar could absorb phosphate from the solution as a potential phosphorus reservoir of soil. Therefore, biochar could effectively balance the leaching and loss of P in phosphate fertilizer (Xu et al. 2016b; Hass et al. 2012; Farrell et al. 2014; Hong et al. 2018; Yang and Lu 2021). Besides, biochar

Table 2 Pearson correlation coefficients between soil acidity, available P (KCl-P, Olsen-P, and DGT-P), chemical forms P (Al-P, Fe-P, and Ca-P), and total P in different tissues (root, straw, and grain) of rice

	pH	Ex-acid	KCl-P	Olsen-P	DGT-P	Al-P	Fe-P	Ca-P	Root-TP	Straw-TP	Grain-TP
pH	1	−0.072	−0.360	0.437	−0.403	0	−0.354	0.343	−0.650	−0.330	−0.336
Ex-acid	−0.499	1	−0.613	−0.670	−0.787*	−0.643	−0.664	−0.359	−0.025	−0.614	−0.780*
KCl-P	0.002	0.388	1	0.553	0.607	0.915**	0.792*	−0.194	−0.005	0.427	0.636
Olsen-P	0.167	−0.570	0.340	1	0.482	0.819*	0.434	0.183	−0.363	0.119	0.302
DGT-P	0.049	−0.072	−0.709	−0.253	1	0.533	0.672	0.158	0.434	0.603	0.773*
Al-P	−0.183	−0.402	0.252	0.891**	−0.098	1	0.686	−0.107	−0.218	0.278	0.527
Fe-P	−0.195	−0.297	0.241	0.870*	0.042	0.947**	1	0.382	0.419	0.855*	0.746
Ca-P	0.274	−0.887**	−0.507	0.565	0.156	0.449	0.387	1	0.329	0.635	0.200
Root-TP	0.823*	−0.317	0.037	−0.034	−0.267	−0.464	−0.464	0.199	1	0.672	0.475
Straw-TP	0.822*	−0.158	0.437	0.256	−0.229	−0.024	−0.068	0.018	0.672	1	0.794*
Grain-TP	0.502	−0.294	0.522	0.644	−0.493	0.399	0.323	0.323	0.475	0.794*	1

The lower left corner represents the correlation in the seedling stage, and the upper right corner represents the correlation in the tillering stage

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

Table 3 Pearson correlation coefficients between soil acidity, available P (KCl-P, Olsen-P, and DGT-P), chemical forms P (Al-P, Fe-P, and Ca-P), and total P in different tissues (root, straw, and grain) of rice

	pH	Ex-acid	KCl-P	Olsen-P	DGT-P	Al-P	Fe-P	Ca-P	Root-TP	Straw-TP	Grain-TP
pH	1	−0.903**	0.789*	0.853*	0.301	0.524	0.158	−0.251	−0.204	0.374	0.639
Ex-acid	−0.523	1	−0.784*	−0.726	−0.270	−0.430	−0.340	0.075	−0.093	−0.495	−0.859*
KCl-P	0.353	−0.808*	1	0.880**	−0.274	0.727	0.128	−0.594	−0.201	0.169	0.498
Olsen-P	0.332	−0.823*	0.812*	1	−0.154	0.854*	0.315	−0.490	−0.173	0.299	0.464
DGT-P	0.384	0.366	−0.281	−0.297	1	−0.388	0.007	0.408	0.020	0.427	0.401
Al-P	−0.125	−0.637	0.805*	0.527	−0.619	1	0.509	−0.632	0.069	0.430	0.347
Fe-P	−0.319	−0.426	0.725	0.424	−0.578	0.913**	1	0.239	0.813*	0.806*	0.649
Ca-P	−0.390	−0.425	0.389	0.330	−0.350	0.689	0.635	1	0.512	0.095	0.116
Root-TP	−0.475	−0.057	0.296	−0.126	−0.313	0.647	0.793*	0.654	1	0.672	0.475
Straw-TP	0.278	−0.452	0.696	0.168	−0.088	0.687	0.678	0.300	0.672	1	0.794*
Grain-TP	0.334	−0.753	0.703	0.364	−0.334	0.799*	0.572	0.532	0.475	0.794*	1

The lower left corner represents the correlation in the filling stage, and the upper right corner represents the correlation in the mature stage

*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level

activated the P availability by promoting microbial reproduction and improving soil phosphatase activity (Pheav et al. 2005). Clustering heatmap showed that the straw treatments and biochar treatments could be clustered a branch, respectively, especially in the mature stage, which indicated that the addition of straw and biochar had different impacts on soil acidity and P availability over a longer period (Fig. 6).

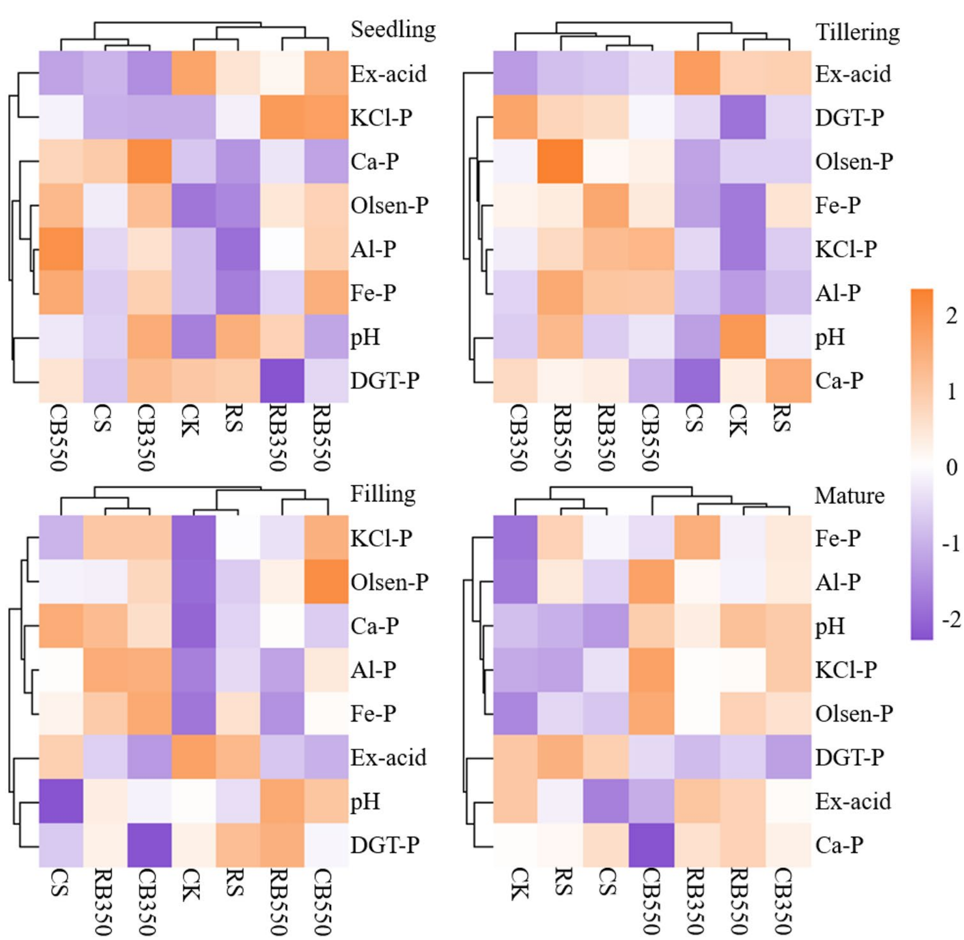

Fig. 6 Clustering heatmap of the soil acidity and P availability under straw returning and carbonization returning in different stages of rice growth

4.3 Effect of straw and biochar on uptake and utilization of P for plants

Biochar not only had a great improvement on soil acidity and P availability but also influenced P utilization by plants (Gao and DeLuca 2018; Xu et al. 2016b; Madiba et al. 2016). This study showed that the relation of total P content in the root, straw, and grain of rice was as follows: grain > straw > root. The total P contents in straw and grain were higher under the RB350 treatment and both had a significantly positive correlation ($R = 0.79$, $p < 0.05$). Biochar treatments increased the total P contents in straw and grain significantly. However, it was worth noting that only RB350 treatment increased the total P content in root significantly, which was because of the migration of most nutrient elements to grains and straw in the ground at the mature stage of rice. These results were proved by significant positive relationships between the soil properties and total P in different tissues of rice. In the seedling stage, the total P of root and straw was positively correlated with soil pH, with the coefficients of 0.82 ($p < 0.05$) (Table 2). In the other stages, the total P in rice was mainly positively correlated with the inorganic P in soils, especially the Al-P and Fe-P. Therefore, straw and biochar treatments promoted the uptake of P in the ground part of plants and improved the utilization rate of P. Biochar could not only supplement soil nutrients, but also optimize soil aggregate structure, retain water and nutrients effectively, and improve soil fertility. The improvement of soil properties had a positive effect on agricultural production, crop yield, and quality (Zwetsloot et al. 2016; Rose et al. 2019; Manolikaki et al. 2016).

5 Conclusions

This study conducted a pot experiment to contrast the dynamic effects of straw and corresponding biochar on the acidity and P availability of Ultisol. Results demonstrated that soil pH, available P, and Al-P decreased with the rice growth, while Fe-P increased. Biochar treatments showed more obvious effects on inhibiting soil acidification and improving available P than straw returning. The application of biochar also increased the contents of Al-P and Fe-P by changing the complexation between phosphate and metal ions. The straw biochar pyrolyzed at 550 ℃ had a larger effect on the available P, while the chemical forms of P were affected mostly by the straw biochar pyrolyzed at 350 ℃. Meanwhile, the canola stalk biochar showed a more obvious influence than that of rice straw biochar. The increased soil pH induced by biochar was the main reason for the increase in soil P availability. On the other hand, the improvement of P supply capacity from soil solid phase to pore water and adsorption–desorption rate also revealed the reason why biochar improved soil P availability, especially in the late period of rice growth. Biochar also increased the total P contents of straw and grain more significantly than straw returning. Therefore, biochar had a better improvement on soil acidity, P availability, and crop yield than straw treatment. The DGT technique and DIFS model provided strong evidence to reveal the changes of P availability with the plant growth in the biochar-amended soils, which was instructive to understand the transportation mechanism of available P in soil.

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Declarations

Conflict of interest The authors declare no competing interests.

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