Rice-husk Biochar Improved Soil Properties and Wheat Yield on an Acidified Purple Soil

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Abstract. Purple soil is one of important agricultural soils in China. However, widespread soil acidification and soil fertility decline have limited the sustainable use of the purple soil in recent decades. Biochar, derived from agricultural waste such as rice husk, shows great potential for controlling soil acidification and fertility improvement of acidified soils. In this study, pot experiment was conducted to investigate the impact of rice-husk biochar application on soil properties and wheat yield on an acidified purple soil. The results showed that soil pH under treatments of 0.5%, 1%, 2% and 5% biochar application was respectively increased by 0.2, 0.4, 0.5 and 1.2 units than that of the treatment without biochar application. Conversely, soil available iron content after biochar application was significantly reduced by 23.6%, 41.5%, 65.4% and 96.0%, respectively. Furthermore, biochar applications increased soil available phosphorus content by up to 115 mg/kg from 20 mg/kg under treatment without biochar application. The improved soil properties after biochar application resulted in significantly higher grain yield of wheat (*Triticum aestivum*. L. Varieties Chuanmai45 and Mianyang31). Compared with the control, wheat yield with treatments of 0.5%, 1%, 2% and 5% biochar application was increased by 3.81%, 7.71%, 45.61% and 57.15%, respectively. The response of wheat yield to biochar application was closely correlated with soil available phosphorus and iron content. We therefore concluded that biochar application could improve soil fertility by decreasing soil acidity and iron toxicity, and consequently increasing soil phosphorus availability. These integrated effects thus resulted in better growth and yield of wheat grown in acidified purple soil.

Introduction

As a unique agricultural soil resource, purple soil distributes mainly in Sichuan Basin, China. However, soil acidification, decline of soil fertility on purple soils was widespread in recent decades, mainly due to human activities. These problems restricted the development of sustainable agriculture in the purple soil area. Studies have shown that crop residue return to field could improve soil fertility [1]. Our annual output of crop straw reaches 700-800 million tons, but more than half of these crop residues are abandoned or burned, resulting in environmental pollution, waste of resources and other issues [2]. Alternatively, these crops residues can be burnt for energy. Under the condition of high temperature pyrolysis in an anaerobic tank, the solid by product of burnt residues is biochar [3]. It has many useful characteristics including high alkalinity, large porosity, large specific surface area, high water holding capacity and high anti-biodegradability. Thus, biochar is expected to use in agricultural areas for soil amendment and improvement, producing slow-release fertilizer carrier, and soil carbon sequestration [4]. Therefore, crop straw and other agricultural waste can be transformed into biochar application to fields. By doing so, it presents an important agricultural practice for improving soil fertility, conserving resources, protecting the environment, and thus promoting the development of sustainable agriculture.

The special properties of biochar make it become an important soil conditioner for agricultural applications. Biochar is rich in organic carbon. For example, biochar contains more than 60% of

carbon element, so biochar application can increase the content of soil organic carbon and soil organic matter (SOM) [5]. Then it can increase the C/N ratio of the soil which can enhance the capacity of holding nutrient and improve soil fertility [6]. Biochar also contains many kinds of mineral nutrient elements, such as phosphorus, potassium, calcium, magnesium, sodium, silicon and so on [7]. Furthermore, the biochar made from livestock and poultry manure has higher content of mineral nutrient elements [8]. This biochar applied to soil can increase the content of mineral nutrients in soil. Generally, biochar is alkaline and contains many base cations. These cations can decrease the content of hydrogen and aluminum cations through exchange reaction [9]. Hence, it can work as a soil conditioner for acidic soil to reduce the soil acidity and increase soil pH [5], and improve the soil fertility [10]. Biochar application can increase the total porosity of the soil, reduce soil bulk density, and reserve more water in the soil profile. Thus biochar application can promote the water uptake of plants, and thus reduce the moisture loss [11]. This could enhance drought resistance and reduce soil erosion [12]. Because of the strong adsorption, the large cation exchange capacity and related chemical properties, biochar can be used as a carrier to slowly release nutrient in fertilizer. In this way, biochar can delay the release of fertilizer nutrient elements, and reduce the nutrient loss of applied fertilizer (such as nitrogen), and improve the nutrients use efficiency [13].

The influence of biochar application on crop growth and yield is varied with the property of biochar, soil types, crop types and environmental conditions. For examples, the yield of corn grown in a sandy soil was increased with the increasing rates of biochar application, with the maximum yield under biochar rate of 15 t/ha [14]. Whereas, biochar application with rates of 5 and 15 t/ha leaded to a reduced production of soybean and corn grown in a volcanic ash soil [15]. One of the possible reasons is that biochar application changed the soil pH and also the availability of soil phosphorus (P) and some trace elements [16].

Purple soil is one kind of moist cambisols according to the soil classification of China, and half is distributed in the Sichuan basin. However, the degradation of purple soils is obvious and widespread, with high susceptivity to drought and erosion, reduction of soil porosity and permeability, soil acidification and heavy metal pollution problems. Furthermore, the nitrogen (N), available P and soil organic matter (SOM) in degraded purple soil were depleted and low [17]. Soil pH is one of the most important factors that affect soil iron (Fe) reduction [18]. In addition, Fe redox reaction is closely related to the distribution of soil N and P and other nutrients, decomposition and transformation of organic matter and so on [19]. Until now, little research has been conducted to study the effect of biochar application on soil improvement and crop growth on purple soil, although the potential is great. Considering that P deficiency and Fe toxicity are two limiting factor of soil fertility on acidified purple soil, we thus assumed that biochar application may improve soil P availability by increasing soil pH and meanwhile decreasing Fe redox.

Rice husk is one of common agricultural wastes in China and many other Asian countries. In this study, biochar made from rice husk was used to study its effect on soil pH, soil available P and Fe in soil, as well as its impact on wheat yield grown in an acidified purple soil under greenhouse condition. By doing so, it can provide theoretical and technical support for scientific and reasonable improvement and enriching the purple soils.

Materials and Methods

Experimental Site and Materials. The experiment was carried out in the National Monitoring Stations of Soil Fertility and Fertilizer Efficiency on Purple Soils (106.4109E, 29.8099N). This station is in east Sichuan Basin within the Three Gorges Reserve, with annual mean temperature of 18.3^{o} C and mean precipitation of 1115 mm. The acidic purple soil used in the experimental soil was collected from the Jiangjin district, Chongqing, China. The initial properties of this soil were as follow: pH, 4.86 (water:soil ratio of 2:1); organic matter content, 19.1 g/kg; 0.5 mol/L $NaHCO_3$-extractable P (Olsen-P), 9.7 mg/kg; and 0.1 mol/L HCl extractable Fe, 114.3 mg/kg. The biochar was prepared at 500℃ pyrolysis condition from rice husk--an agricultural waste during milling. The major properties of this biochar are shown in Table 1.

Table 1 The properties of rice-husk biochar used in this study

Parameter	Organic carbon (g/kg)	Total P (g/kg)	Total Ca (g/kg)	Total Mg (g/kg)	Total SiO_2 (g/kg)	Total Fe (mg/kg)	pH
Biochar	239.7	1.33	2.63	0.38	470	18	10.4

Experimental Design. The layout of this pot experiment was a split plot in randomized complete block design with four replicates. The main treatments consisted of five levels of applied biochar: 0, 0.5%, 1%, 2% and 5% (w/w). The subplot treatment consisted of two wheat cultivars (*Triticum aestivum*. V. Chuanmai45 and Mianyang31). Thus, there were 40 pots in total. The basal rates of fertilization were N 100 mg/kg soil as urea, P_2O_5 100 mg/kg soil as calcium superphosphate, and K_2O 100 mg/kg soil as potassium sulfate.

The used soil was air dried and passed over 2 mm sieve. This soil (2.5 kg soil per pot) and the corresponding amount of biochar and nitrogen, phosphorus and potassium fertilizer were evenly mixed, and added into the plastic pots. Water at equivalence of 20 % gravimetric water content was added to the pots. Seeds of two wheat cultivars were surface sterilized with a solution of 5% H_2O_2 for 30 min. After washing by deionized water, 12 seeds were sown in each pot at 3 cm depth. After emergence, the seedlings were thinned to 6 plants per pot. All of the pots were watered to field water capacity during the experiment. The growth period of wheat in pots was from November 26, 2014 to May 10, 2015, with 165 days in total.

Sampling and Analysis. The plant height, spike number, flag leaf length and other index was determined at harvest stage. The wheat plant was separated into grain, husk, straw, leaf and root, and then they were washed by deionized water and dried to achieve constant weight in the oven at 70℃, following recording their dry weight by electronic balance (Sartorius, Germany).

After picking out the root, soil samples were evenly mixed and collected, and then air dried for use further. The properties of soil samples were measured by using conventional methods [19]: soil pH was determined with a pH meter (Leici, China) with the soil/water ratio of 1:2.5; soil organic matter was measured by potassium dichromate volumetric-outside heating method; soil available P (Olsen-P) was extracted by 0.5 mol/L sodium bicarbonate, and then measured by Mo-Sb Anti spetrophotography method; soil available Fe was extracted by 0.1 mol/L hydrochloric acid and then measured by Atomic Absorption Spectroscopy (General, China).

Statistical Analysis. Data were processed by Microsoft Excel 2010 software. One-factor ANOVA procedure in SPSS software (SPSS 21, USA) was used for statistical analysis. Means were separated by Fisher's protected least significance difference (LSD) test at $P<0.05$. Regression models were used to evaluate the response using SigmaPlot (Systat software, USA).

Results

Effect of Biochar Rates on Wheat Yield. Table 2 showed that the application of biochar significantly increased wheat straw and grain weight. The results of ANOVA analysis indicated that the straw weight and grain weight of Chuanmai45 under the treatments of BC0.5% and BC1% were increased by 3.8% and 7.7%, but had no significant difference with control (BC0%). When the rate of biochar application reached 2% (BC2%), the straw and grain weight of two wheat cultivars was significantly increased than that of control, which was 45.6% higher than control. When the rate of biochar reached 5% (BC5%), the wheat yield reached the highest which was 57.2% higher than the control treatment. However, the grain yield had no significant difference between BC2% and BC5% treatment. Compared with control, biochar application increased the grain yield by 32.6% in average.

For variety Mianyang31, all of biochar applications expect BC0.5% treatment resulted in significant increase in straw and grain weight than the control treatment. When the rate of biochar reached 5%, the wheat yield reached the highest which was 50.8% higher than the control treatment.

However, the grain yield had no significant difference between BC2% and BC5% treatment. Compared with control, biochar application increased the grain yield by 36.7% in average.

Table 2 Wheat biomass as affected by different biochar rates

Variety	Treatment	Biomass (g/pot)					Root-to-shoot ratio	Harvest index (%)
		Straw	Leaf	Husk	Grain	Root		
Chuanmai45	BC0%	9.5b	3.7b	5.5a	12.4b	0.73a	0.024	39.9
	BC0.5%	10.3b	4.0ab	5.4a	12.9b	0.74a	0.023	39.6
	BC1%	10.0b	3.9ab	5.8a	13.4b	0.69a	0.021	40.3
	BC2%	11.4a	4.2a	6.6a	18.1a	0.79a	0.020	45.0
	BC5%	11.6a	4.3a	6.2a	19.5a	0.73a	0.018	46.9
Mianyang31	BC0%	9.8b	5.1a	5.7c	13.0c	0.82a	0.024	38.8
	BC0.5%	10.1b	4.1a	6.0c	14.1c	0.82a	0.024	41.0
	BC1%	12.8a	5.0a	7.4ab	17.4b	0.79a	0.019	40.8
	BC2%	13.2a	4.5a	7.6a	19.6a	0.78a	0.017	43.6
	BC5%	12.4a	4.7a	6.4bc	19.9a	0.78a	0.018	45.9

Note: Harvest index is the percentage of grain weight to the shoot weight (straw + leaf + husk +grain). Values followed by different letters within the same column mean significant difference ($p<0.05$).

The biochar application had little effect on the leaf and husk weight of the two wheat cultivars (Table 2). Meanwhile, application of biochar had no significant effect on the root weight, but the root-to-shoot ratio was decreased from 0.024 to 0.018. This indicated that the application of biochar significantly promoted the biomass accumulation of the shoot parts of two wheat cultivars. Conversely, compared with the control treatment, biochar application increased the harvest index of wheat from 39.9 to 46.9 for Chuanmai45, and from 38.8 to 45.9 for Mianyang31, respectively.

The Table 3 showed that the height and spike number of Chuanmai45 and Mianyang31 was increased by biochar applications, when comparing with the control. But there was no significant difference between different rates of biochar application. Biochar application significantly increased the plant height of Mianyang31, whereas had no significant effect on spike number. Compared with the control, application of biochar significantly reduced the flag leaf length and spike length of Chuanmai45. When the rate of biochar application is higher than 2%, flag leaf length of Chuanmai45 was significantly decreased. For example, length of flag leaf with 5% biochar was reduced by 17.5% than that of the control. Biochar application has no significant effect on spike numbers, although there was an increasing trend (Table 3).

Table 3 Wheat growth characteristics as affected by different biochar rates

Variety	Treatments	Plant height (cm)	Flag leaf length (cm)	Spike length (cm)	Spike number per pot
Chuanmai45	BC0%	74.1a	17.7a	13.4ab	10.5a
	BC0.5%	77.7a	16.3ab	13.4ab	11.0a
	BC1%	76.0a	16.2ab	13.0bc	11.8a
	BC2%	76.6a	15.4b	13.7a	11.5a
	BC5%	77.8a	14.6b	12.8c	11.3a
Mianyang31	BC0%	73.3b	16.5a	13.1b	12.3ab
	BC0.5%	78.2a	16.4a	13.9a	10.8b
	BC1%	79.5a	16.0a	14.1a	12.8ab
	BC2%	78.6a	15.9a	14.1a	13.8a
	BC5%	78.4a	13.4b	13.0b	12.8ab

Note: Values followed by different letters within the same column mean significant difference ($p<0.05$).

Effects of Biochar Application on Soil Properties. As shown in Table 4, the soil acidification was inhibited to some degree after the application of biochar, and the pH values of this acidified purple soil were increased with the increasing rate of biochar application. The treatment with 5% of

biochar application resulted in highest pH value which was increased by more than 1 unit than the control. At the same time, application of biochar had the potential to increase the soil organic matter, especially under high rate of biochar application.

Furthermore, soil available P content (Olsen-P) was greatly increased by biochar application. For variety Chuanmai45, the soil Olsen-P contents were increased from 19.9 mg/kg under the control to maximum 118.2 mg/kg under the 5% biochar application. The averaged increase of biochar on soil Olsen-P 50.6% was as high as 214%. Similar results were also shown for the variety Mianyang31 (Table 4). In converse, soil available Fe content was obviously decreased by biochar application. For variety Chuanmai45, the soil available Fe content was decreased from 120.9 mg/kg under the control to minimum 4.8 mg/kg under the 5% biochar application. The reduction of soil available Fe content due to increasing rates of biochar application was 20.0%, 31.5%, 56.8%, and 92.4%, respectively. Similar results were also shown for the variety Mianyang31 (Table 4).

Table 4 Soil properties as affected different biochar rates

Variety	Treatment	pH	Organic matter (g/kg)	Available P (mg/kg)	Available Fe (mg/kg)
Chuanmai45	BC0%	4.8e	19.9b	19.9e	120.9a
	BC0.5%	5.0d	19.6b	30.0d	92.5b
	BC1%	5.2c	19.7b	42.2c	70.7c
	BC2%	5.3b	19.8b	59.7b	41.9d
	BC5%	6.0a	22.0a	118.2a	4.8e
Mianyang31	BC0%	4.9e	18.2c	19.5e	107.6a
	BC0.5%	5.0d	19.3bc	30.4d	86.0b
	BC1%	5.1c	19.9b	40.3c	73.6c
	BC2%	5.2b	20.2b	56.5b	46.4d
	BC5%	5.9a	21.8a	111.9a	8.2e

Note: Values followed by different letters within the same column mean significant difference ($p<0.05$).

Relationships between Wheat Yield and Soil Properties. The application of biochar significantly increased the grain yield of two wheat varieties (Table 2). Furthermore, Fig. 1 showed that the correlation between biochar rate and wheat yield was highly significant ($r_{Chuanmai} = 0.91$, $P < 0.01$; $r_{Mianyang} = 0.93$, $P < 0.01$). These regression equations indicated that biochar application with rate of 4.66% for Chuanmai45 or 3.57% for Mianyang31 would harvest the highest grain yield (Fig. 1).

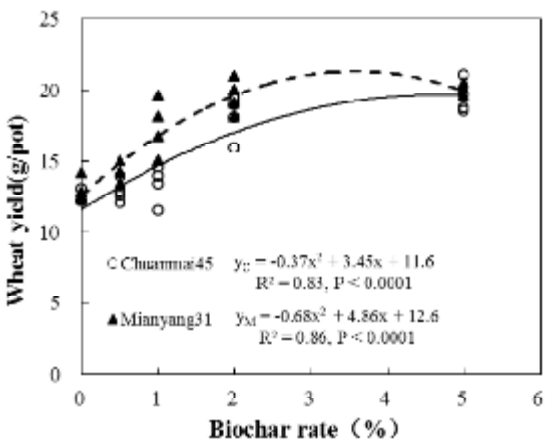

Fig. 1 Relationships between wheat yield and rate of biochar application

The increased grain yield of two wheat varieties was also related with the improved soil

properties due to biochar application (Fig. 2). The grain yield of the two wheat varieties was positively correlated with the soil pH values, both with high determination coefficients (R^2=0.71, 0.80). The regression equations also showed that the optimal soil pH for growth is 6.9 for Chuanmai45, while 5.6 for Mianyang31, respectively. Soil organic matter also affected the grain yield but to less extent because their correlation was low. The soil Olsen-P was significantly and positively correlated with the grain yield of two wheat varieties, both with high determination coefficients (R^2=0.80, 0.86). These equations indicated that the improvement of soil P status by biochar application is important to recover the productivity of the acidified purple soil. At the same time, the soil available Fe was significantly but negatively correlated with the grain yield of two wheat varieties, both with high determination coefficients (R^2=0.78, 0.80).

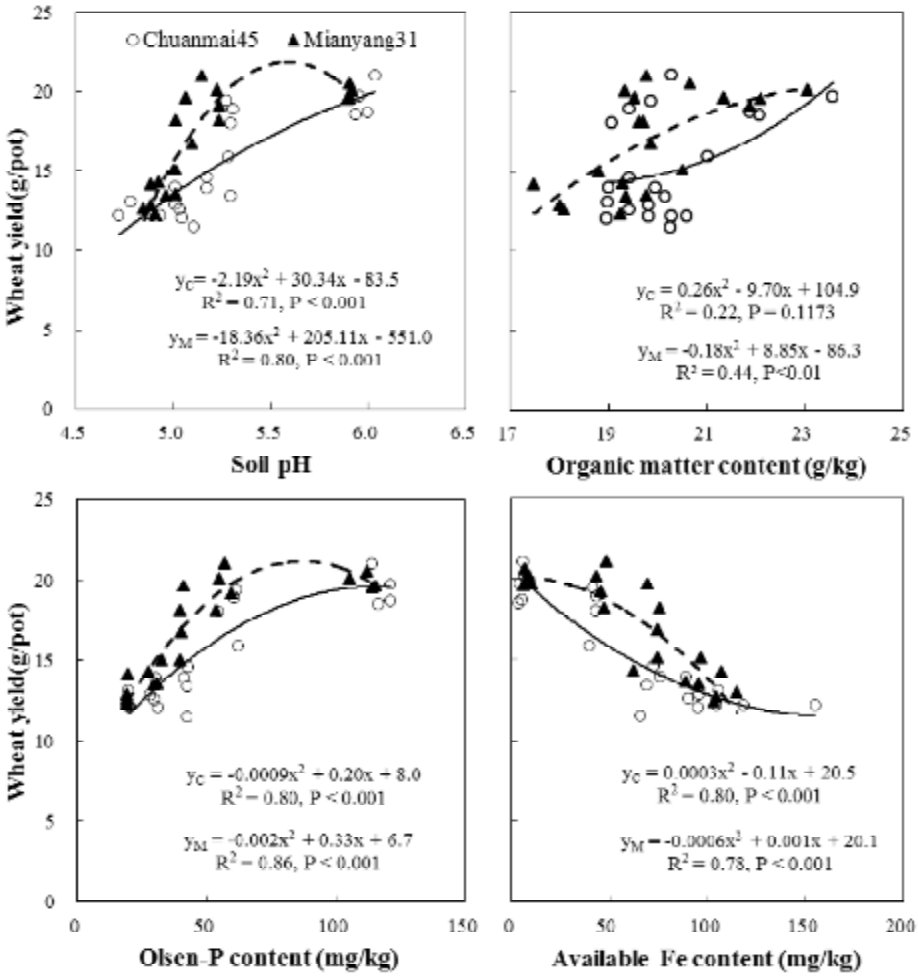

Fig. 2 Relationships between grain yield and soil properties after biochar application

Discussion

Effect of Biochar Application on Yield of Wheat. Previous studies showed that the application of biochar could significantly promote the growth of crops, increase the accumulation of dry matter, and result in higher yield of crops [20]. In this study, the application of biochar significantly increased the wheat straw and grain weight, but had no significant effect on the weight of leaf, husk and root. Thus root-to-shoot ratio showed a decreasing trend. This indicated that biochar application promoted the accumulation of photosynthetic products in wheat shoot biomass, but not for the root. The reason may be that biochar application created a better rhizosphere for better uptake of water and nutrient. Thus it was no need to capture more space by increasing root growth. The harvest index was increased with the increasing rate of biochar application, which indicated that the application of biochar significantly increased the translocation of photosynthetic products to wheat

grain. Such result was consistent with most of the previous studies [6, 21]. However, the effect of the application of biochar on crop yield was not always same due to the different experimental conditions. The influences of biochar application on crop yield may be derived from its effects on soil physical and chemical properties, including increased nutrient availability, better environment for root growth and development [22], and also from the reduced effectiveness of the toxic metal cations [23]. In this experiment, the biochar application increased the content of soil organic matter and Olsen-P, and reduced the available Fe content of the soil, improved the growth condition. As an integrated response to biochar application, the shoot biomass and finally the grain yield of wheat was promoted.

Effect of Application of Biochar on Growth and Development of Wheat. In agriculture, biochar is mainly used to increase the soil fertility, improve the growth environment of crops and the quality of agricultural products. The porosity and strong adsorption properties of biochar in soil are proved to be good for the activity and reproduction of soil microbes and be good for reducing their survival competition [24]. It can promote the water absorption by plants and thus reduce moisture loss [25], and then promote the growth of plants. Such a unique structure and physicochemical properties of biochar thus can increase soil organic carbon, improve soil fertility, but also by changing the physical and chemical properties of soil further impact on plant growth and development [26]. In this study, under the conventional fertilization, height of wheat plant is increased by biochar application, comparing with the control. But biochar application did not significantly affect the spike length and number, but did significantly decrease the length of flag leaf under high rates of biochar application. Liu et al. studied the effects of black carbon on corn seedling growth and nutrient uptake and nutrient leaching. Their results showed that black carbon could improve the seeding growth of corn. For example, the plant height and stem diameter was increased by 4.3-13.1 cm and by 0.4-2.0 mm. And the corn biomass under the treatment of black carbon application was increased from 16.2 to 55.1 g/pot [27]. Thus, both the type and rate of applied biochar can affect the germination of wheat seeds and seedling growth [28].

Effects of Biochar on Soil Properties. Generally, biochar is alkaline and contains abundant base cations. After applying it into the soil, the degree of base saturation can be improved. Through the exchange reaction of these base cations, the content of hydrogen and aluminum cations can be reduced [29]. This study showed that the pH of this acidified purple soil was significantly increased after application of biochar (Table 4). There is also abundant organic carbon in biochar, which can increase the content of organic matter in soil, improve soil structure and physical and chemical properties as well as the ability to hold the water and fertilizer [3]; then it can increase the C/N ratio of the soil which can increase the soil capacity of holding nutrient. In this study, the application of biochar significantly increased the soil organic matter and available phosphorus content. On the one hand, the nutrient content of biochar itself may determine the effect of the biochar to improve the soil fertility [30]. In this study, the coefficient between the total P of the used rice-husk biochar and the soil available P content was 0.999 ($p<0.01$, data is not shown). And increasing the rate of biochar application can lineally increase the available P content of purple soil (Table 4). On the other hand, the biochar can indirectly affect the soil nutrient availability through improving the physical and chemical properties of the soil. Because the biochar has high porosity, larger specific surface area and strong adsorption, it can increase the adsorption capacity for heavy metals in contaminated soils [29]. And thus biochar application can reduce the biological effectiveness of heavy mental elements, achieving the objective of soil restoration. In our study, the increased grain yield of wheat after application of rice-husk biochar was closely related with the soil available Fe. It’s well known that soil with low pH values is easy to cause Fe toxicity to plants. Thus, decreased soil available Fe due to biochar application would be one of important reasons for better grain yield of the two wheat varieties. Furthermore, grain yield of two wheat varieties was also correlated with soil available P content. Biochar has strong adsorption properties and a lot of negative charge, it can increase the soil cation exchange capacity [31], and through to provide a negative charge or adsorption the elements such as iron and aluminum of combined with phosphorus, and improve the effectiveness of the phosphorus element in the soil [32]. Thus, the reason would be that rice-husk

biochar is naturally rich in plant-available P element after pyrolysis. The other reason would be that the immobilized P by Al^{3+}, Fe^{2+}/Fe^{3+} under acidified condition was mobilized after biochar application. Taken together, biochar application increased the growth and the grain yield of two wheat cultivars because of reduced soil acidification and Fe toxicity, but increased soil P availability.

Conclusion

Application of biochar made from rice husk improved the soil fertility of the acidified purple soil through decreasing the soil acidity and the Fe toxicity as well as increasing soil organic matter and especially soil available P content. As the same time, biochar application improved the growth and the final grain yield of two wheat varieties grown in acidified purple soil. This increased grain yield of wheat after biochar application is related with the change of soil properties at lest including decreased soil acidity, reduced Fe toxicity and increased soil P availability all of which are limiting factors for wheat cropping.

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