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Article

A Field Experiment on Enhancement of Crop Yield by Rice Straw and Corn Stalk-Derived Biochar in Northern China

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Abstract: Biochar, a green way to deal with burning and burying biomass, has attracted more attention in recent years. To fill the gap of the effects of different biochar on crop yield in Northern China, the first field experiment was conducted in farmland located in Hebei Province. Biochars derived from two kinds of feedstocks (rice straw and corn stalk) were added into an Inceptisols area with different dosages (1 ton/ha, 2 ton/ha or 4 ton/ha) in April 2014. The crop yields were collected for corn, peanut, and sweet potato during one crop season from spring to autumn 2014, and the wheat from winter 2014 to summer 2015, respectively. The results showed biochar amendment could enhance yields, and biochar from rice straw showed a more positive effect on the yield of corn, peanut, and winter wheat than corn stalk biochar. The dosage of biochar of 2 ton/ha or 1 ton/ha could enhance the yield by 5%–15% and biochar of 4 ton/ha could increase the yield by about 20%. The properties of N/P/K, CEC, and pH of soils amended with biochar were not changed, while biochar effects could be related to improvement of soil water content.

Keywords: biochar; crop yield; field experiment; Northern China

1. Introduction

Burning straw in air brings many environmental problems by emitting inhalable particles and gaseous pollutant. It is now one of the main origins of the air pollution in China. In a system of combustion simulation-dilution tunnel sampling, crop straw flaming emitted 7.2–39.0 g/kg of PM2.5 (particulate matter size less than 2.5 μm), and in a smoldering combustion situation the PM2.5 emission was even 2.4–11.5 times higher [1]. In 2006, straw burning caused 2.17 Mt PM2.5 with a mass of gaseous organic and greenhouse gas pollutant [2]. In China, more than 60% of total PAHs were estimated from incineration of biomass and agricultural straw reached 1/3 of incinerating biomass [3]. In addition to direct burning, the other way to deal with straw is returning it back to the fields. Although such treatment could promote soil properties and enhance crop productivity [4], the respiration of soil was also stimulated. Zhao *et al.* [5] investigated that soil respiration could be affected by tillage and crop residue management. Deep moldboard plough and crop residue retained increased soil respiration by 41.9% and 21.0% during winter wheat season and summer maize season, respectively.

Different from direct burning or returning biomass residues to farmland, scientists proposed another way to make biomass charcoal, also called biochar, to be a soil enhancer. Biochar is a product of carbonized biomass during pyrolysis, which was first found in the Central Amazon basin [6]. Now biochar is considered more as an effective carbon sequestration material. In Lehmann *et al.*'s prediction models, emission of CO_2 reduced by about 20% with black carbon retained in soil over 100 years. Okimori *et al.* [7] also suggested that biomass waste could reduce CO_2 emission. In soil science studies, researchers focus on the potential of biochar on the enhancement of crop yield [8,9] and biochar-soil, biochar-soil biota interactions [10].

Recent researches showed that biochar amendment could increase water-holding capacity of soil as well as nutrient-holding ability because of its developed porosity structure, high specific surface area, and CEC. Additionally, the characteristics of soil and the climate of the planting area, crop productivity is also related to feedstock, pyrolysis conditions, and dosage of biochar addition [11]. This is the reason why researchers obtained different results in some field experiments. For example, positive results suggested biochar amendment improved crop yield [12–15]. Baronti *et al.* [16] found that yields increased both in wheat fields in Central Italy and maize fields in Northern Italy when coppiced woodlands-derived biochar was added in soils at the rate of 10 ton/ha. In Indonesia, the addition of biochar increased the yield of plants [17]. Olmo *et al.* [18] investigated that olive-tree pruning-derived biochar amendment was related to a higher yield but the nutrient content was not obviously affected. The study in Kaoma, Zambia, Africa showed that maize cob-derived biochar dramatically increased maize yield by over 100% in different soils [19]. In Australia, the types and dosages of fertilizer and the existence of microbes could influence the effect of oil mallee charcoal on wheat yield [20].

On the contrary, some researchers suggested that the biochar-amended soil did not promote plant yields, even decreased the productivity at a higher dosage or with some different feedstock, neither in pot nor site experiment [16,21–25]. For example, Rajkovich *et al.* [26] carried out a greenhouse pot trial and suggested that animal manure biochar and food waste biochar decreased the yield of corn at a high dosage (7%), while lower rates (2%, 0.5%) of biochar could increase the yield. Cornelissen *et al.* [19] also showed that in Mkushi and the other two experiments in Zambia, neither maize cob nor wood biochar affected the maize yields. Jones *et al.* [27] conducted a three-year field experiment and found that commercial wood chip biochar affected little on maize yield in the first year and on grass yield in the second year, but enhanced grass yield in the third year. Similar result from the study of Major *et al.* [28] showed that maize yields were increased by commercial wood biochar in the second year.

In the past five years, scientists in China had paid more attention to biochar use in agriculture soils. Liu *et al.* [29] suggested that rapeseed and sweet potato yields were increased by 36.02% and 53.77%, respectively, if wheat straw biochar was added into soil at a dosage of 40 ton/ha in Jiangxi Province in Southern China. Zhang *et al.* [30] concluded that wheat straw biochar could enhance rice yield both in fertilized and unfertilized paddy in Tai Lake plain. Liu *et al.* [31] conducted a five-crop-season field experiment and found that wheat straw biochar could enhance the crop yield in Henan Province, Central Great Plain of China.

All of reported data in China at present were mostly in Southern China where acidic ultisols is distributed. Nevertheless, the soils and climates in Northern China are quite different from that in Southern China. Herein, to fill the gap of the effect of corn stalk and rice straw-derived biochar on crop yields in Northern China, we performed a field experiment in Hebei Province.

2. Experimental Section

2.1. Soil Type and Climate of the Study Area

The field experiment was started from April 2014 in agricultural lands in Fengnan County, Tangshan City, Hebei Province (39°30′47″ N, 118°15′38″ E, Northern China), located in a warm temperate continental monsoon climate region (Figure 1). The soil type in the study area is an inceptisol, based on U.S. Department of Agriculture. According to literature reports [32], during years 1961–2011, the annual rainfall was of 600 mm–700 mm. The precipitation was 500 mm–600 mm in 2014 and average temperature of the year 2014 was 12 °C–14 °C. The above data was recorded from reports of the Hebei Province Meteorological Bureau.

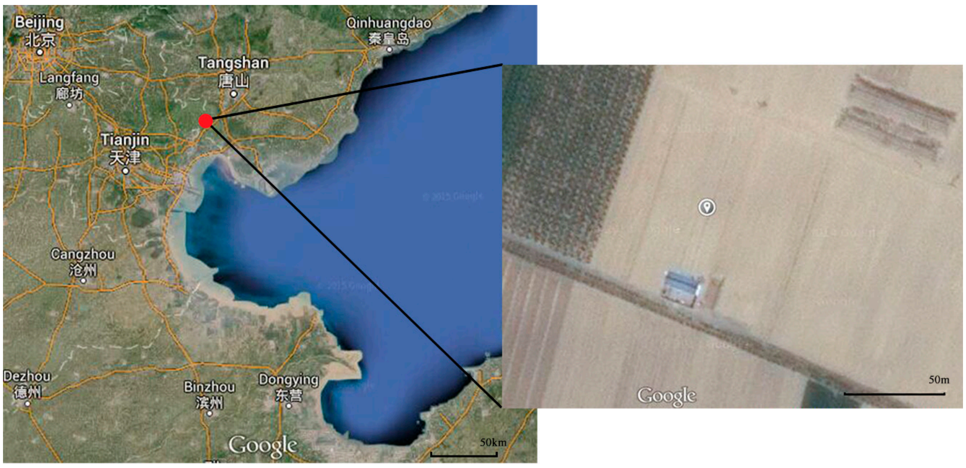

Figure 1. The location of the study area.

2.2. Biochar

Corn and rice are the main crops in the study area. We chose these two abundant biomass, corn stalk and rice straw, to make biochar in a kiln near the farmland, which was used to produce commercial charcoal with wood chips. It could create an air-limited condition so that the feedstocks could slowly pyrolyze. The pyrolysis temperature was about 450 ± 50 °C. A whole pyrolysis progress lasted one week with two tons of biochar product. The biochar derived from corn stalk and rice straw were characterized using an elemental analyzer (EA-3000, Euro VECTOR) as listed in Table 1.

Table 1. Analyses of biochar derived from corn stalk and rice straw.

Biochar	C (%)	H (%)	O (%)	N (%)
Corn stalk biochar	71.7	3.7	16.5	2.4
Rice straw biochar	63.5	1.6	9.2	1.3

2.3. Field Experiment

The site field was divided into three parts for planting peanuts (P), sweet potatoes (S) and corn (C). Biochar from different feedstock was added into soils at the time of sowing with dosages (1 ton/ha, 2 ton/ha or 4 ton/ha) in ridges with blank column, as shown in Figure 2. The width of each column was about 1 m, and the length of each column depended on practical field conditions. Herein, corn and sweet potato columns were about 100 m in length, while peanut columns were about 83 m length. After the rain on 26 April 2014, corn was sown two days later. The routine cultivates with compound fertilizer (N/P/K) and acetochlor (50%) was added at the rate of 750 kg/ha and 2–3 L/ha, respectively. Peanut was sown two days after corn with the same treatment and furthermore, 3 L/ha of atrazine (20%) was added on 22 June according to growth situation of crop in the fields. Sweet potatoes were planted on 7 May after biochar and compound fertilizer (N/P/K, 450 kg/ha) were added. With five months of common farming practicing, crops were harvested in September to October 2014 (peanut on 6 September, sweet potato on 8 October), then the yield data was collected in each condition. In spring season tests, the yield was harvested as a lump without replication, while in winter, each condition was replicated in triplicate to collect the yield data.

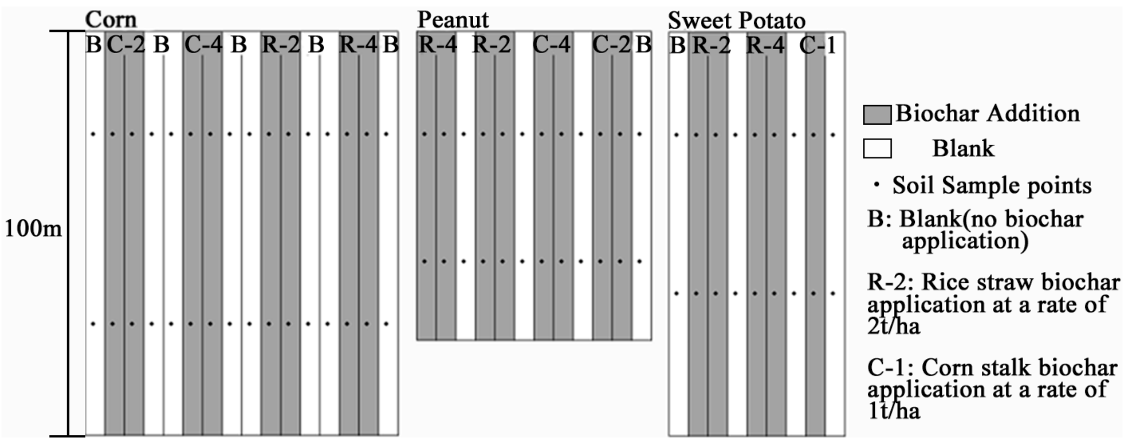

Figure 2. Sketch map of the field experiment design and soil sampling sites.

After autumn harvest, winter wheat was planted during 7 October 2014 to 21 June 2015 in the area where peanut was just planted. Meanwhile, N/P/K compound fertilizer was applied at 600 kg/ha. No more biochar was added during this sowing. There were three rounds of irrigation during the winter wheat cropping season, on 5 November 2014, on 6 May 2015, and on 1 June 2015, respectively.

Fertilizer dressing (CON_2H_4 and N/P/K fertilizer at 300 kg/ha each) and herbicide (3.75 L/ha atrazine (20%)) was added during 6–8 May, 2015. The photo of the land scenery is illustrated in Figure 3.

(**a**) (**b**)

Figure 3. Snapshot of sweet potato on 26 July 2014 (**a**) and winter wheat on 10 October 2014 (**b**).

2.4. Soil Sampling and Analysis

Soil samples were taken from the topsoil with 0 cm–15 cm depth on 26 July 2014, after about two months following biochar addition. The samples points were shown in Figure 2.

The soil samples were dried at room temperature and ground to less than 1 mm. Soil pH was measured in 1:2.5 soil/DI water. The soil pH is around 7. Fractions of heavy metals were measured by BCR sequential extraction method [33] and analyzed by ICP-OES (Spectro Blue, Germany). The cation exchange capacity (CEC) was determined by ammonium acetate extract method.

Total N was analyzed following the Kjeldahl procedure (NY/T 53-1987, national standard method). Total P was analyzed following the method NY/T 83-1988.Total K was analyzed following the method NY/T 87-1988.

Two kinds of biochar were mixed with soil in the lab at different rates (1%, 2%, and 10%) to measure the soil water-holding capacity (WHC). WHC was measured according to the method by Outi Priha [34]. Independent *t*-test was used to confirm if different treatments affect WHC by GraphPad Prism version 6.00 for Mac OS X (GraphPad Software, La Jolla, CA, USA).

3. Results and Discussion

3.1. Biochar Effects on Crop Yield

The crop yields in the field experiments were collected and are displayed in Table 2. The data showed that biochar addition could enhance the crop yields. The yield of the corn on the control soils without biochar weighed 0.5 ton/ha. Obviously, corn stalk-derived biochar (CB) increased the corn yield to 12.18 ton/ha and 12.6 ton/ha by the dosage of 2 ton/ha and 4 ton/ha biochar adding, respectively. Similarly, rice straw-derived biochar (RB) increased the corn yield to 12.36 ton/ha and 12.96 ton/ha by the dosage of 2 ton/ha and 4 ton/ha, respectively. In comparison to the corn yield of 4.2 ton/ha without biochar amendment, CB enhanced the peanut yield to 4.68 ton/ha and 5.1 ton/ha at the dosage of 2 ton/ha and 4 ton/ha, respectively. Likewise, 2 ton/ha and 4 ton/ha RB raised the peanut yield to 4.98 ton/ha and 5.22 ton/ha, respectively. Interestingly, similar to the corn yield, RB could enhance more peanut yield than CB. In addition, the sweet potato yield was also affected by adding biochar. For example, with 2 ton/ha RB addition, sweet potato yield was 37.62 ton/ha and with 4 ton/ha biochar that was 38.94 ton/ha, while without biochar the yield was only 33 ton/ha. Furthermore, compared with the effect of CB on the corn and the peanut, CB affected much more on sweet potato yield. Even at a dosage of 1 ton/ha, CB could improve sweet potato yield to 39.6 ton/ha.

For winter wheat, the yield was 8.6 ± 1.25 and 6.9 ± 2.01 ton/ha with CB addition at rate of 2 ton/ha and 4 ton/ha, respectively. Whereas RB increased the yield from 7.7 ± 0.09 ton/ha to 9.0 ± 0.55 ton/ha with the biochar of 2 ton/ha to 4 ton/ha.

Table 2. Yields of different crops on biochar amended soil *.

Crop Type and Sowing Time to Harvest Time	Crop Yield (ton/ha)	Crop Yield with Corn Stalk Derived Biochar (CB) (ton/ha)			Crop Yield with Rice Straw Derived Biochar (RB) (ton/ha)	
	No biochar	1 ton/ha CB	2 ton/ha CB	4 ton/ha CB	2 ton/ha RB	4 ton/ha RB
Corn April–October 2014	10.5	Not designed	12.18	12.6	12.36	12.96
Peanut April–September 2014	4.2	Not designed	4.68	5.1	4.98	5.22
Sweet potato May–October 2014	33	39.6	Not designed	Not designed	37.62	38.94
Winter wheat October 2014–June 2015	7.16 ± 1.59	Not designed	8.6 ± 1.25	6.9 ± 2.01	7.7 ± 0.09	9.0 ± 0.55

* Only the sum of yield data without replication (April–October 2014) is shown; For tests with replication in triplicate (October 2014–June 2015), the data showed the mean and standard deviation values of the yield.

According to above productivity harvest, it is obvious that higher dosage of both kinds of biochar has a more positive effect on crop yields. Compared with other field scale experiments about the effect of biochar application on crop yields (Table 3), of which most suggested that the addition enhanced the yield, the rate of increase in our study was about 11%–25% higher than most studies, except for the yield that was increased by over 100% than that reported by Yamato *et al.* [17]. According to the soil taxonomy map from U.S. Dept. of Agriculture, the soil in the study of Manuel Olmo *et al.* [18] was similar to the soil in our study and the results were similar that biochar increased the yield by about 20%.

Table 3. Summary of the field experiments on crop yield by biochar amendment.

Site Location	Crop Type	Biochar: Feedstock	Biochar: Dosage (ton/ha)	Yield ($ton\ ha^{-1}$): Without Biochar	Yield ($ton\ ha^{-1}$): Adding Biochar	Reference
Empoli, Toscana, Central Italy	durum wheat	coppiced woodlands (beech, hazel, oak, birch)	10	2.4	3.1	Silvia Baronti *et al.*, 2010 [16]
Beano, Friuli Venezia Giulia, Italy	maize			9.7	10.3	
Santa Cruz, Córdoba, southern Spain	durum wheat	olive-tree prunings	40	4.42 ± 0.14	5.61 ± 0.24	Manuel Olmo *et al.*, 2014 [18]
the organic Student Farm at the University of California, Davis, U.S. (38.55 N, 121.74 W)	lettuce	walnut shells	5	1.11 ± 0.06	1.08 ± 0.08	Emma C. Suddick *et al.*, 2013 [25] *
Houay-Khot, northern Laos	upland rice	wood residues and rosewood	4	1.8	1.9	Hidetoshi Asai *et al.*, 2009 [24]
			8		2.0	
			16		1.8	
Long-Or, northern Laos			4	4.5	4.2	
			8		4.7	
			16		4.7	
Abergwyngregyn, Wales, UK (53°14′ N, 4°01′ W)	fodder maize	chipped trunks and large branches	25	26 ± 1	25 ± 1	D.L. Jones *et al.*, 2012 [27]
			50		26 ± 1	
Jiangsu Province, China (31°24′ N, 119°41′ E)	rice	wheat straw	10	9.1 ± 0.63	9.9 ± 0.22	Afeng Zhang *et al.*, 2010 [30]
			40		10.2 ± 0.36	
Tifton, GA, U.S. (31°30′ N, 83°32′ W)	corn	peanut hull	11	13.004	13.422	Julia W. Gaskin *et al.*, 2010 [22]
			22		11.679	
		pine chip	11	15.127	14.523	
			22		13.645	
South Sumatra, Indonesia	maize	bark of *Acacia mangium*	37	4.69 ± 2.17	14.97 ± 1.11	Masahide Yamato *et al.*, 2006 [17] *
	cowpea			5.16 ± 0.63	12.94 ± 0.63	
	peanut			2.84 ± 0.30	5.61 ± 0.43	
Wollongbar Agricultural Institute, Australia	sweet corn	poultry litter	5	3.3 ± 0.6	3.5 ± 1.0	L. Van Zwieten *et al.*, 2008 [35]
			10		4.8 ±0.4	
			20		4.6 ±1.4	
			50		6.2 ±1.8	
the Iowa State University Boyd Research Farm, Boone County, Iowa, U.S.	maize	mixed hardwood (primarily oak, elm and hickory) woodchips	19.2	6.83 ± 1.01	7.59±1.28	Natalia Rogovska *et al.*, 2014 [36] *
			38.3		8.02 ± 3.06	
			57.5		10.15 ± 1.03	
			76.6		10.04 ± 0.72	
			95.8		10.54 ± 0.79	

Table 3. *Cont.*

Site Location	Crop Type	Biochar		Yield (ton ha^{-1})		Reference
		Feedstock	Dosage (ton/ha)	Without Biochar	Adding Biochar	
Llanos Orientales, Colombia (04°10′15.2″ N, 72°36′12.9″ W)	maize	wood	8	4.83 ± 0.16	4.81 ± 0.08	Julie Major *et al.*, 2010 [28] *
			20		4.71 ± 0.12	
Pindar, Western Australia	wheat	oil mallees	1.5	1.872	1.787	Paul Blackwell *et al.*, 2007 [20]
			3		1.889	
			6		1.809	
Manaus, Amazonas, Brazil (3°8′ S, 59°52′ W)	rice	secondary forest wood	11	1.20 ± 0.11	2.00 ± 0.14	Christoph Steiner *et al.*, 2007 [37] *
Shannxi Province, China (108°24′ E, 34°20′ N)	maize	wheat straw	0.1	0.98 ± 2.24	1.07 ± 0.17	Zhang Na *et al.*, 2015 [38]
			0.5		1.06 ± 0.20	
			1		1.05 ± 0.19	
Henan Province, China (34°32′ N, 115°30′ E)	maize	wheat straw	20	6.65 ± 0.006	7.86 ± 0.05	Afeng Zhang *et al.*, 2012 [39]
			40		7.42 ± 0.07	
Quino-Chufquén area, Chile (38°22′ S, 72°37′ W)	barley	oat hull	5	2.17 ± 0.15	2.38 ± 0.06	G. Curaqueo *et al.*, 2014 [40]
			10		2.53 ± 0.11	
			20		2.85 ± 0.05	
Pumalal area, Chile (38°38′ S, 72°29′ W)			5	2.35 ± 0.16	2.59 ± 0.06	
			10		2.75 ± 0.12	
			20		2.87 ± 0.06	
Nyankpala, the Northern Region of Ghana (9°25′ N, 00°58′ W)	maize	rice husk	2	1.03 ± 0.04	1.67 ± 0.04	Ammal Abukari, 2014 [41] *
			4		2.79 ± 0.04	
Merelbeke, Belgium (50°58′ N, 3°46′ E)	spring barley	hard- and softwood	20	5.90 ± 0.09	5.87 ± 0.11	Victoria Nelissen *et al.*, 2015 [42]
Thoothukudi District, India	maize	not mentioned	5	7.11	1.09	B.Gokila *et al.*, 2015 [43]
			7.5		1.14	
Parma, North, Italy (44°48′23″ N, 10°16′30″ E)	tomato	slow pyrolysis	14	88.33	86.20	F.P Vaccari *et al.*, 2015 [44]
		fast pyrolysis			92.29	
Shanxi Province, China (38°29′ N, 112°72′ E)	maize	wheat straw	20	9.06 ± 0.58	10.58 ± 0.53	Dengxiao Zhang *et al.*, 2015 [45]
			40		10.14 ± 0.49	

* Data was estimated from the figures in the paper.

3.2. Biochar Effects on N/P/K, CEC, and pH of Soils

In our study area, even though the addition of biochar enhanced the yields of crops, it did not affect on the total content of N/P/K in soils (Table 4). Likewise, cation exchange capacity (CEC), as an important index to evaluate soil fertility, was not much changed by biochar in this case (Table 4). The similar results were also investigated in the study of Borchard *et al.* [21]. However, more studies investigated that biochar could enhance the soil nutrient stocks [15,16]. From Table 4, the value of pH was somehow decreased a little by the biochar addition, especially in peanut-planted soil. However, to some extent, we suggested that the pH of soils was not changed after biochar amendment in such a period of time. It is known that water plays an important role in Northern China because of the limit rainfall there. Thus, we consider that biochar application may enhance crop yield by holding more water in the soil and the WHC results in our lab experiment showed that biochar addition could increase soil water content, especially at a high rate (10%) of application. Change of soil WHC with biochar addition at rates of 1% and 2%, which were similar to the application in the field in our study, seemed to not be significant (statistical test), but as it has been reported by Sun *et al.* in 2014 [46], straw biochar could significantly increase the available water content of soils. Kristiina Karhu mentioned that biochar application could increase WHC by 11% [47]. Ammal Abukari also suggested that biochar addition increased soil moisture content [41]. For this aspect, we will keep the study and further investigate whether the biochar can enhance the soil moisture content and water uptake.

Table 4. The determination of N/P/K, CEC, and pH of soils.

Biochar Dosage	P (%)	N (%)	K (%)	CEC (cmol/kg)	pH
Soil without biochar	0.0515	0.071	2.58	4.92 ± 0.52	7.06
Corn Land Soil					
2 ton/ha CB	0.050	0.041	2.39	4.15 ± 0.34	6.97
4 ton/ha CB	0.059	0.061	2.50	4.23 ± 0.33	6.91
2 ton/ha RB	0.047	0.067	2.26	4.32 ± 0.20	6.81
4 ton/ha RB	0.065	0.078	2.37	4.62 ± 0.71	6.97
Peanut Land Soil					
2 ton/ha CB	0.067	0.074	2.57	5.36 ± 1.47	6.24
4 ton/ha CB	0.066	0.082	2.09	5.70 ± 0.22	6.19
2 ton/ha RB	0.045	0.043	2.32	5.36 ± 0.16	7.03
4 ton/ha RB	0.053	0.057	2.25	4.79 ± 0.78	6.43
Sweet Potato Land Soil					
2 ton/ha RB	0.054	0.072	2.31	4.15 ± 1.28	7.10
4 ton/ha RB	0.058	0.065	2.26	5.31 ± 0.93	7.15

4. Conclusions

The first field experiment of biochar application in Hebei Province, Northern China, focused on the effects of rice straw and corn stalk-derived biochar on the crop yields of corn, peanut, and sweet potato during one crop season from spring to autumn 2014, and wheat from winter 2014 to summer 2015, respectively. The yield in the first season could be measured after biochar amendment and rice straw-derived biochar showed a more positive effect on the yield of corn, peanut, and winter wheat than corn stalk biochar. A lower dosage of biochar (2 ton/ha or 1 ton/ha) could enhance yields by 5%–15% and biochar of 4 ton/ha could increase yields by about 20%. The properties of N/P/K, CEC, and pH of soils were not changed before and after biochar addition and we consider such yield enhancement of biochar effects could be related to improvement of soil water content rather than elements. Further investigation on this study area is on the way. Due to the present results, further investigation will focus on the biochar effect on physical and chemical properties of the soil and the mechanism of crop yield variation.

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Author Contributions

Yang Yang performed the laboratory analysis and wrote the manuscript; Yang Yang, Shaoqiang Ma, Yi Zhao, Ming Jing, and Yongqiang Xu were responsible for field sampling and crop yield collection; Jiawei Chen designed the study, supervised the experiments and revised the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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