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Effects of Organic Amendments on the Improvement of Soil Nutrients and Crop Yield in Sandy Soils during a 4-Year Field Experiment in Huang-Huai-Hai Plain, Northern China

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Abstract: To address the low productivity of sandy farmlands, our study aimed to conduct a comparative study on the effects of different organic amendment (OA) inputs for the potential improvement of crop yield and soil quality in sandy alkaline farmlands through the selection of a suitable OA. This study set up straw (ST) returning as control and chemical fertilizer (CF) treatment as a side control, and chose three OAs returning as treatments, including pig manure (PM), biogas residue (BR), and straw biochar (BC), for improving soil fertility, with all amendments having matched doses of nitrogen (N). The experiment was conducted at the Wuqiao Experimental Station (37°41 N, 116°37 E) of China Agricultural University in Hebei Province, China, from October 2012 to September 2016. The cropping rotation was the winter wheat (*Triticum aestivum* L.)-summer maize (*Zea mays* L.) rotation system. Through a consecutive four-year field experiment, the principal results showed that three types of OA application significantly increased soil organic carbon from 1.46 g kg^{-1} to 8.24 g kg^{-1}, soil total N from 0.21 g kg^{-1} to 0.64 g kg^{-1}, soil available potassium from 55.85 mg kg^{-1} to 288.76 mg kg^{-1}, and soil available phosphate from 4.86 mg kg^{-1} to 65.00 mg kg^{-1} in the 0–20 cm soil layer. The BR was the most effective in improving soil nutrients as compared with the ST. The PM and BR treatments were more conducive to promoting crop yield by 6–20% than ST, and the BC treatment significantly reduced the yield of winter wheat by 19% and summer maize by 8%. As the BR and PM treatments improved the soil nutrient content and significantly increased crop yield, these were the top choices for transforming the low-yield sandy farmlands.

Keywords: medium- and low-yield farmland; alkaline sandy soil; organic amendments; soil chemical properties; yield

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1. Introduction

There has been an increase in the land application of organic amendments (OA) such as manure, biosolids, green wastes, and composts because of their potential to boost soil carbon (C), improve fertility, help mitigate climate change, support soil health, and for regenerative agriculture [1–5]. China has been facing enormous pressure caused by conflicts among land resources, population resources, and the environment for a long time [6]. Under similar climatic conditions, the grain yield of most cultivated lands is much lower than the potential productivity of high-yield farmlands, and most cultivated lands can close yield gaps through water management and nutrient application [7,8]. With grain yield as one of the main factors that restrict agricultural land productivity, medium- and low-yield farmlands occupy as much as 79% of the limited cultivation areas in China [9].

Therefore, the input of OA into agricultural ecosystems could be used to control soil quality and to make rational use of agricultural wastes, consequently, closing yield gaps.

The transformation of medium- and low-yield farmlands is mainly achieved using feasible agricultural measures to improve the level of farmland production, so that these farmlands could gradually become high-yield croplands. Land productivity of the middle- and low-yield fields in China could be increased by 19% and 24%, respectively, through one prediction method by using the Moderate Resolution Imaging Spectroradiometer [9]. Analyses through the spatial autocorrelation analysis and the geographical information system (GIS) technology show that the potential grain yield of the Huang-Huai-Hai (3H) plain could reach 33.05 million tons, of which the transformation of medium- and low-yield fields accounted for 73.04% of the increase in grain yield [10]. It can be seen that middle- and low-yield farmlands in China have great potential to increase production and income through an effective transformation using currently feasible technological processes. The best way to develop high-quality soils is to manage crops and grounds to promote build-up and maintenance of high organic matter levels, specifically, the right amount of active organic matter using OA [11]. The OA can provide high concentrations of essential plant nutrients and help increase soil quality [2,12], which is very suitable for the improvement of medium- and low-yield farmlands. Modification of medium- and low-yield farmlands by improving soil quality can alleviate the shortage of agricultural cultivation land and improve total grain yield.

With the increasing interest in using OA, its application for fertility and productivity to restore or improve farmland is also growing, and the demand possibly increases with the challenges posed by global changes. The use of OA benefited yields and enhanced resilience of agricultural systems as shown by an exhaustive meta-analysis including 132 long-term ($\geq$10 years) studies in the world [13]. The OA offered some environmental benefits such as increasing soil carbon, aboveground net primary productivity, soil water holding capacity, and plant tissue nitrogen (N), and a global meta-analysis of 92 studies included some of the environmental harms caused by OA [1]. The OA provided 25% to 80% additional C input to the soil, and there was no or slightly significant difference in physicochemical and biological soil properties among OA adopting a 37-year field experiment [14]. A combination of organics and fertilizers is the most effective way to build up soil organic matter, produce more food, and enhance sustainability, especially in dryland farming systems, as shown by an analysis of 32 long-term experiments in China [15]. Organic waste recycling through the application of OA which can reduce the environmental burden and mitigate environmental impacts arising from discharge of OA-derived pollutants could be effective in using nutrient resources and ameliorating soil quality, thus enhancing farmland productivity and increasing crop yield. This is of great importance for the improvement of medium- and low-yield fields and food security in China [1,4,12].

Based on the background of the transformation of medium- and low-yield alkaline sandy farmlands and OA use, this study selected straw (ST), pig manure (PM), biogas residue (BR), and biochar (BC) by equal nitrogen input. Currently, there are many studies on the effects of OA such as BC, ST, BR, PM, and cow manure on soil quality and yield. However, there are relatively few experiments involving medium- and low-yield alkaline sandy farmlands and the comparison of various OAs at the same time. Therefore, this experiment carried out a comparative study on the effects of different OA inputs for the potential improvement of crop yield and soil quality in sandy alkaline farmlands. The experiment selected winter wheat-summer maize as the object under study, conventional ST as the control, and chemical fertilizer (CF) as the side control. This study aimed to screen out suitable OAs for the improvement of soil quality and crop yield in alkaline sandy farmlands, which is of great practical significance for medium- and low-yield farmland transformation and food security in China.

2. Materials and Methods

2.1. Site Description, Climate, and Soil

The experiment began in October 2012 at the Wuqiao Experimental Station, China Agricultural University (37°41 N, 116°37 E) in Hebei Province, China. The total precipitation was 562 mm y^{-1}, and the mean annual temperature was 12.9 °C. The soil was classified as sandy soil, composed of 84.09% sand, 9.73% silt, and 6.18% clay (World Reference Base for Soil Resources). The soil total nitrogen (STN) for 0–20 cm was 0.21 g kg^{-1}, soil available phosphate (SAP) was 4.86 mg kg^{-1}, soil available potassium (SAK) was 55.85 mg kg^{-1}, soil organic carbon (SOC) was 1.46 g kg^{-1}, and soil pH was 8.71. The SOC content was determined by the $K_2Cr_2O_7$ oxidation method using an exogenous thermal process [16]. The STN concentration was measured by the semi-micro Kjeldahl method and through an automatic nitrogen analyzer [17]. The SAP concentration was measured by the Olsen method by extraction with sodium bicarbonate [18] and SAK was determined using ammonium acetate and measured by flame photometry [19]. The planting pattern was classified as the conventional winter wheat-summer maize rotation system. Jimai-22 is the winter wheat variety and zhengdan-958 is the summer maize variety. The monthly average precipitation and temperatures during the experimental period are shown in Figure 1.

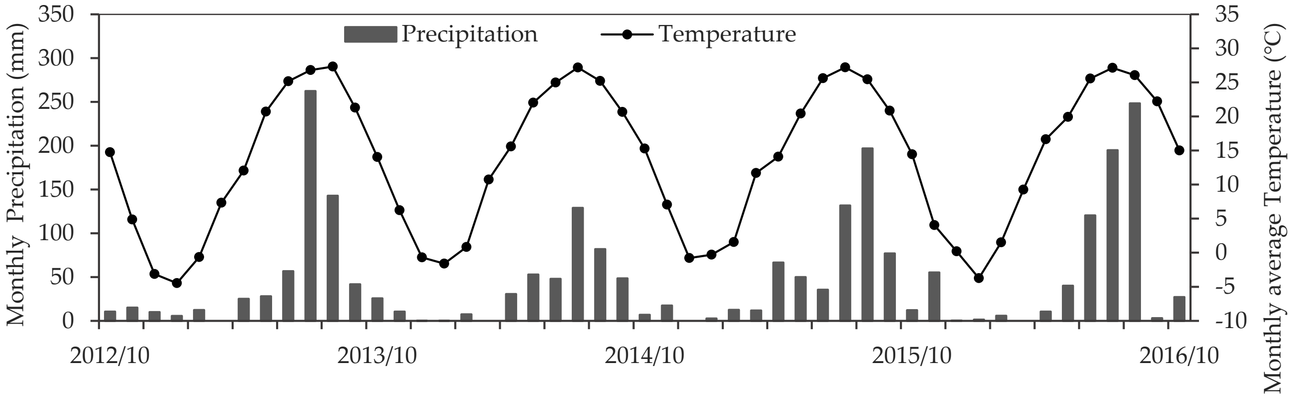

Figure 1. Monthly Precipitation and temperature during the period of 2012/10–2016/9 at the Wuqiao Experimental Station of China Agricultural University.

2.2. Experimental Design

Based on the principle of equal nitrogen input, PM, BR, and BC were returned to the field with ST returning as the control and CF as the side control. Five treatments were performed using a random block design. Each treatment was repeated three times, and the field plot size was 5.1 m × 4 m. BR was produced. In an anaerobic environment, BR is the residue after biogas produced by microbial fermentation of organic matter such as pig manure, cow manure, and straw. Biochar is obtained by crushing wheat straw into semi-closed biomass carbonization furnace and pyrolysis carbonization at 500 °C. The chemical properties of OA are listed in Table 1.

Table 1. Nutrient contents and pH of organic amendments.

Treatments	C (%)	N (%)	P (%)	K (%)	C/N	pH
Maize straw	43.00	0.70	0.20	2.05	61.43	6.14
Wheat straw	37.80	0.56	-	-	67.50	6.12
Biogas residue	17.40	1.90	1.69	0.60	9.16	7.20
Pig manure	18.20	1.96	3.42	0.90	9.29	7.08
Biochar	38.70	1.34	0.20	3.70	28.88	9.36

Note: The nutrients and pH in the organic amendments were mixed analyses performed using the composite samples. The nutrient contents were expressed on a dry weight basis through calculation.

In this experiment, a winter wheat yield of 7500 kg ha^{-1} and a summer maize yield of 9000 kg ha^{-1} were used as objectives, and the amount of crop straw produced on this basis was returned to the field as the standard. Based on the carbon content of the returned ST, the carbon-nitrogen ratio (C/N) of the other materials, and the actual situation of OA application in the farmland, the BC was fully returned to the field with the carbon content of ST. In contrast, PM and BR were returned to the field with half of the carbon content of the returned ST. The treatment with the highest nitrogen content (BR) was used as the standard to return an equal amount of nitrogen to the field, and the missing part was supplemented by CF. The specific nitrogen fertilizer scheme is shown in Table 2.

Table 2. Experimental design of fertilization.

Treatments		**Application Rate (kg ha^{-1} year^{-1})**	**Added C (kg ha^{-1} year^{-1})**	**Added N (kg ha^{-1} year^{-1})**	**Inorganic N-Based Application Rate (kg ha^{-1} year^{-1})**		**Total N (kg ha^{-1} year^{-1})**	**C/N**
					Wheat	**Maize**		
Straw	maize	9000	3870	63	442	419	966	6.94
	wheat	7500	2835	42				
Biogas residue		19,267	3352	366	300	300	966	3.47
Pig manure		18,420	3352	361	305	300	966	3.47
Biochar		17,326	6705	232	434	300	966	6.94
Chemical fertilizer		-	-	-	300	300	600	-

During the four-year experiment from 2013 to 2016, soil fertility was observed in real time. In this experiment, nitrogen fertilizer was divided into base fertilizer and topdressing fertilizer. The ratio of base fertilizer for the wheat season (sowing date) to topdressing fertilizer (jointing stage) was 6:4, and the ratio of base fertilizer of maize season (sowing date) to topdressing fertilizer (jointing stage) was 4:6. Phosphorus fertilizer was applied at a dose of 150 kg ha^{-1} of P supplied as diammonium phosphate, and 150 kg ha^{-1} of K fertilizer supplied as potassium sulphate during the wheat and maize seasons, respectively, on the sowing date. In accordance with the characteristics of sandy-loam soils and climate, the irrigation method was adopted several times and adjustable. The irrigation scheme of wheat was 75 mm at sowing, 50 mm at turning-green, 50 mm at flowering, and 50 mm at grain filling. The irrigation scheme of maize was 75 mm at sowing, and 45 mm at flowering. The tillage method was carried out once before wheat sowing. The OA and CF were applied before sowing and were mixed with the topsoil through tillage, in which wheat straw was returned to the field at the maize seedling stage and was covered on the soil surface [12,20,21].

2.3. Soil Sampling and Analysis

After the summer maize harvest (October) from 2012 to 2016, soil samples were collected from two layers, 0–10 cm and 10–20 cm from the surface, according to the W-shaped five-point sampling method. The five-point soil samples from the same layer and plot were mixed evenly to obtain a soil sample. Soil samples were taken back to the laboratory to remove impurities such as residual plant roots and gravel, and then divided into two parts and air-dried naturally. One air-dried soil sample was sieved through a 1 mm filter for the determination of SAP and SAK, and the other was sieved through a 0.25 mm filter for the determination of SOC and STN. We calculated the bulk density by drying the soils at 105 °C. Finally, the SOC stock (*SOCs*), STN stock (*STNs*), SAP stock (*SAPs*), and SAK stock (*SAKs*) were calculated using the following formula [22]:

$$SOCs = \sum_i^m SOCi \times Bi \times Di \times 10 \quad (1)$$

$$STNs = \sum_i^m STNi \times Bi \times Di \times 10 \quad (2)$$

$$SAPs = \sum_{i}^{m} SAPi \times Bi \times Di \times 10 \tag{3}$$

$$STNs = \sum_{i}^{m} STNi \times Bi \times Di \times 10 \tag{4}$$

where *SOCs* (t ha^{-1}), *STNs* (t ha^{-1}), *SAPs* (kg ha^{-1}), and *SAKs* (kg ha^{-1}) are the stocks of SOC, STN, SAP, and SAK. The *SOCi* is the SOC concentration on the *i*th layer (g kg^{-1}), *STNi* is the STN concentration on the *i*th layer (g kg^{-1}), *SAPi* is the SAP concentration on the *i*th layer (mg kg^{-1}), and *SAKi* is the SAK concentration on the *i*th layer (mg kg^{-1}). *Bi* is the bulk density of the *i*th layer (g cm^{-3}), and *Di* is the thickness of this layer (cm). The bulk density of this experiment is specified in Table S1.

The upside plants of the winter wheat and summer maize were taken at the maturity stage. The aboveground biomass was first dried at 105 °C for 1–2 h, and then at 80 °C to constant weight. In the winter wheat harvest period, a 1.5 m × 3 m sample without disruption was selected to calculate the yield and yield components. In the harvest period of summer maize, 3 m × 1.8 m plants without disruption were selected. All sampling was not carried out at the edge of the plot.

2.4. Statistical Analysis

The results were initially collated using Excel 2016 (Microsoft, Redmond, USA). One-way analysis of variance (ANOVA) was performed using SPSS 20.0 (SPSS, Chicago, USA). Multiple comparisons were made using Duncan's test. Statistical analysis was performed using the Statistical Analysis Software package (SAS Institute, North Carolina, 2011).

3. Results

3.1. Soil Organic Carbon

The SOC is the core representative of soil fertility. Increasing SOC plays an essential role in improving soil productivity, ensuring food security, and mitigating climate change. Compared with the initial SOC contents (1.46 g kg^{-1}), returning OA to the field significantly increased the organic matter level of the medium- and low-yield alkaline sandy fields (Figure 2). With the increase in repeated OA applications, the SOC with BC treatments was significantly higher than that with other OA treatments, while that with CF was the lowest. In the 0–10 cm soil layer, the BC increased by 1.84 g kg^{-1} $year^{-1}$, BR by 0.57 g kg^{-1} $year^{-1}$, PM by 0.48 g kg^{-1} $year^{-1}$, and ST by 0.54 g kg^{-1} $year^{-1}$ after four years of continuous OA return. In the 10–20 cm soil layer, BC increased by 1.55 g kg^{-1} $year^{-1}$, BR was 0.42 g kg^{-1} $year^{-1}$, PM was 0.35 g kg^{-1} $year^{-1}$, and ST increased by 0.38 g kg^{-1} $year^{-1}$ after four years of continuous OA return. The CF amendment increased the SOC levels by 0.09 g kg^{-1} $year^{-1}$ and 0.03 g kg^{-1} $year^{-1}$ for 0–10cm and 10–20cm soil layers, respectively. Compared with the SOC of ST control, that of the BC treatment increased significantly, but there was no significant difference between the SOC of BR and PM.

3.2. Soil Total Nitrogen

The STN is the sum of various forms of nitrogen in the soil, including organic nitrogen and inorganic nitrogen. Compared with the initial STN (0.21 g kg^{-1}), returning OA to the field significantly increased the nitrogen level of medium- and low-yield alkaline sandy fields (Figure 3). With the increase in repeated OA applications, the STN with BR treatments was significantly higher than other that in OA treatments, while STN was lowest in CF. In the 0–10 cm soil layer, BR increased by 0.12 g kg^{-1} $year^{-1}$, PM was 0.09 g kg^{-1} $year^{-1}$, the BC was 0.09 g kg^{-1} $year^{-1}$, and ST increased by 0.07 g kg^{-1} $year^{-1}$ after four years of continuous OA return. In the 10–20 cm soil layer, BR increased by 0.09 g kg^{-1} $year^{-1}$, BC was 0.05 g kg^{-1} $year^{-1}$, PM was 0.03 g kg^{-1} $year^{-1}$, and ST increased by 0.03 g kg^{-1} $year^{-1}$ after four years of continuous OA return. The CF amendment increased the STN levels by 0.01 g kg^{-1} $year^{-1}$ and 0.00 g kg^{-1} $year^{-1}$ for 0–10cm and 10–20cm soil layers, respectively. With the years of OAs returning to the field, the differences between the treatments were increasing since some of the N fertilizers were supplemented with CF in the experimental scheme, and only a small amount was retained in the soil after fertilization. The differences in STN between the treatments were mainly caused by the N content of the OA. The BR, BC, and PM treatments significantly increased the STN as compared with that of the ST control.

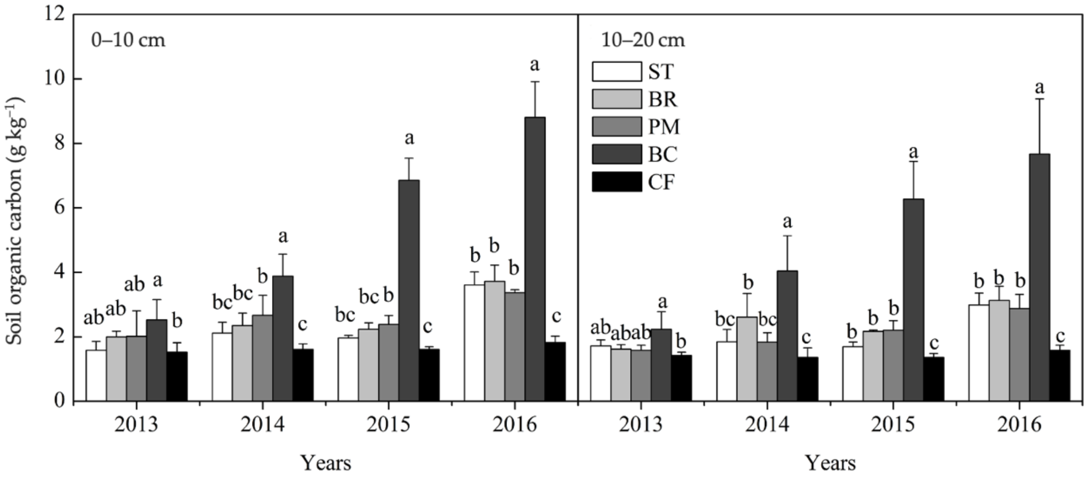

Figure 2. Effect of organic amendment application on soil organic carbon levels during a 4-year field experiment. Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

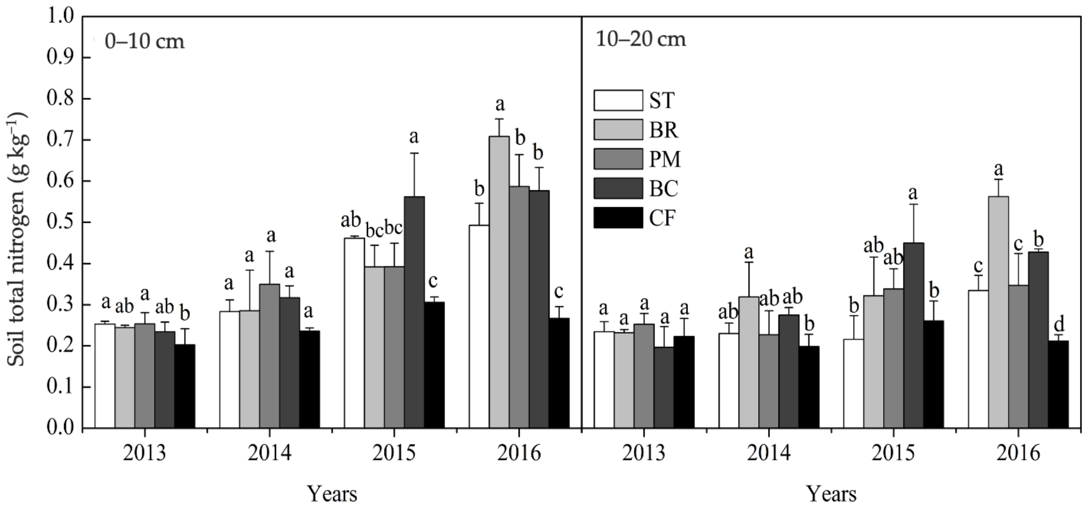

Figure 3. Effect of organic amendment application on soil total nitrogen levels during a 4-year field experiment. Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

3.3. Soil Available Potassium

The sources of SAK included the OA and CF, and the SAK in the OA fluctuated from year to year. After four years of field experiments, the SAK content increased and fluctuated within a certain range, which was closely related to the absorption and use of SAK by crops. Compared with the SAK content of ST control, the BC significantly increased SAK, while that of BR and PM showed no significant difference (Figure 4). This is consistent with the trend of converted SAK content in OA, and the key influencing factors of OA content were identified. In the 0–10 cm soil layer, the BC increased by 56.15 mg kg^{-1} year^{-1}, BR was 26.65 mg kg^{-1} year^{-1}, PM was 23.44 mg kg^{-1} year^{-1}, and ST increased by 25.41 mg kg^{-1} year^{-1} after four years of continuous OA return. In the 10–20 cm soil layer, the BC increased by 60.31 mg kg^{-1} year^{-1}, BR was 19.54 mg kg^{-1} year^{-1}, PM was

1.92 mg kg^{-1} year^{-1}, and ST increased by 11.67 mg kg^{-1} year^{-1} after four years of continuous OA return. CF increased by 15.01 mg kg^{-1} year^{-1} in the 0–10 cm soil layer and decreased by 3.56 mg kg^{-1} year^{-1} in the 10–20 cm soil layer. The SAK in the soils treated with OA could meet the normal growth needs of crops.

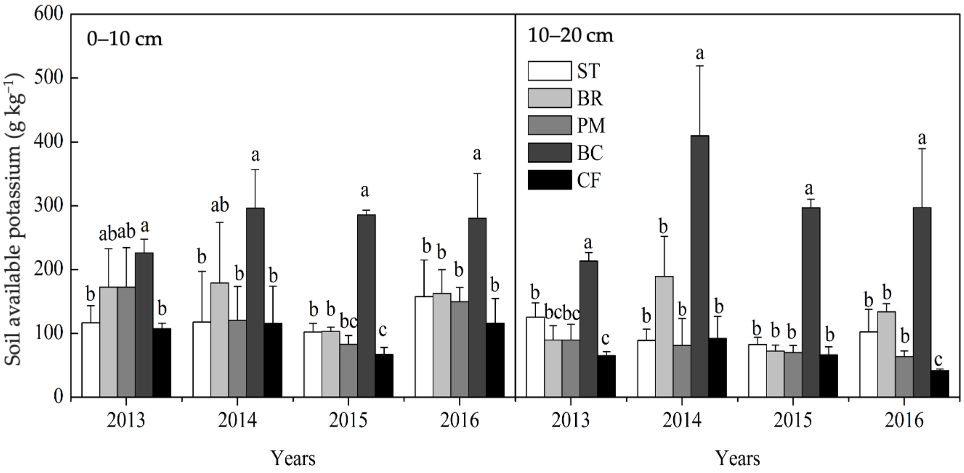

Figure 4. Effect of organic amendment application on soil available potassium levels during a 4-year field experiment. Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

3.4. Soil Available Phosphorus

Adding OAs to medium- and low-yield farmlands for four consecutive years significantly increased SAP, especially in the BR and PM treatments. In the 0–10 cm soil layer, the PM increased by 18.56 mg kg^{-1} year^{-1}, BR by 15.76 mg kg^{-1} year^{-1}, BC by 1.44 mg kg^{-1} year^{-1}, and ST by 2.81 mg kg^{-1} year^{-1} after four years of continuous OA return (Figure 5). In the 10–20 cm soil layer, the PM increased by 11.51 mg kg^{-1} year^{-1}, BR was 9.49 mg kg^{-1} year^{-1}, BC was 0.58 mg kg^{-1} year^{-1}, and ST decreased by 0.13 mg kg^{-1} year^{-1} after four years of continuous OA return. The CF amendment increased the SAP levels by 1.86 mg kg^{-1} year^{-1} in the 0–10 cm soil layer and decreased by 0.21 mg kg^{-1} year^{-1} in the 10–20 cm soil layer. Compared with ST, PM, and BR significantly increased SAP, while PM was slightly better than BR, and BC showed no significant difference. The trend of comparison between SAP in OA and SAP in the experimental results was consistent.

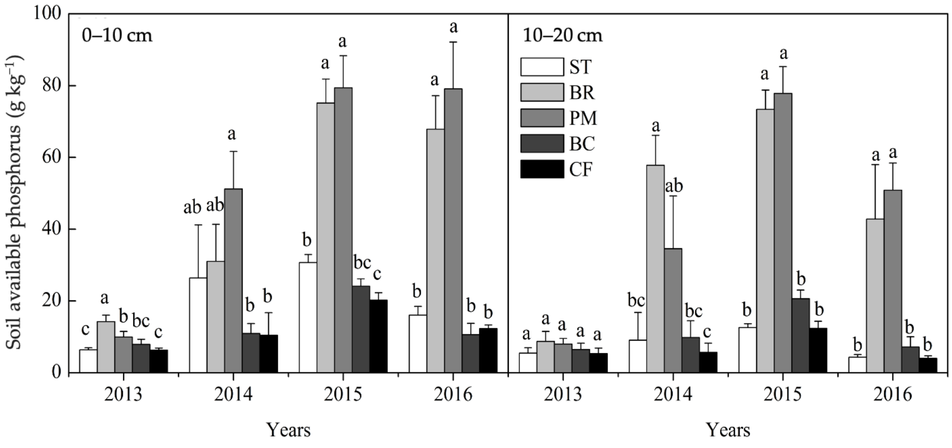

Figure 5. Effect of organic amendment application on soil available phosphorus levels during a 4-year field experiment. Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

3.5. Effects of Organic Amendment Application on Nutrient Storage

After comparing the contents of SOC, STN, SAK, and SAP with the different OAs returning to the field, it was difficult to comprehensively compare the fertilizer effects of the different OAs. Therefore, the nutrient storage of the 0–20 cm (tillage layer) was selected as the effect index of OA fertilization ability to make a comprehensive review. For SOCs, the BC treatment had the best effect in the improvement of medium- and low-yield alkaline sandy fields, which was 2.28 times higher than that of the ST control after four years of experimentation. Meanwhile, the BR, PM, and CF were 1.02, 0.95, and 0.53 times higher than that of ST, respectively (Figure 6). In the process of increasing the test life, the differences between the OAs were gradually revealed. Compared with the SOC level of ST, the BC had the most significant effect on SOC increase. At the same time, the ST and BR were better than PM in increasing SOC rates. For STNs, the BR treatment had the highest value and was 1.51 times higher than that of the ST control after four years of experimentation. Meanwhile, PM, BC, and CF were 1.15, 1.11, and 0.59 times higher than that of the ST, respectively. As a relatively stable N source, the OA can improve the availability of soil nitrogen; thus, the subsequent effects of N become more pronounced. For SAKs, the BC treatment had the highest value and was 2.04 times higher than that of the ST control after four years of experimentation. Meanwhile, the BR, PM, and CF were 1.12, 0.84, and 0.63 times higher than that of the ST, respectively. The SAK content in soil treated with OA could meet the normal growth needs of crops and was consistent with the trend of SAK content in OA. For SAP storage, the PM treatment had the highest value and was 6.44 times that of the ST control after four years of experimentation. Meanwhile, the BR, BC, and CF were 5.32, 0.81, and 0.82 times that of the ST, respectively. The SAP content in the soils treated with BC and ST could not meet the normal growth needs of winter wheat and summer maize for the time being.

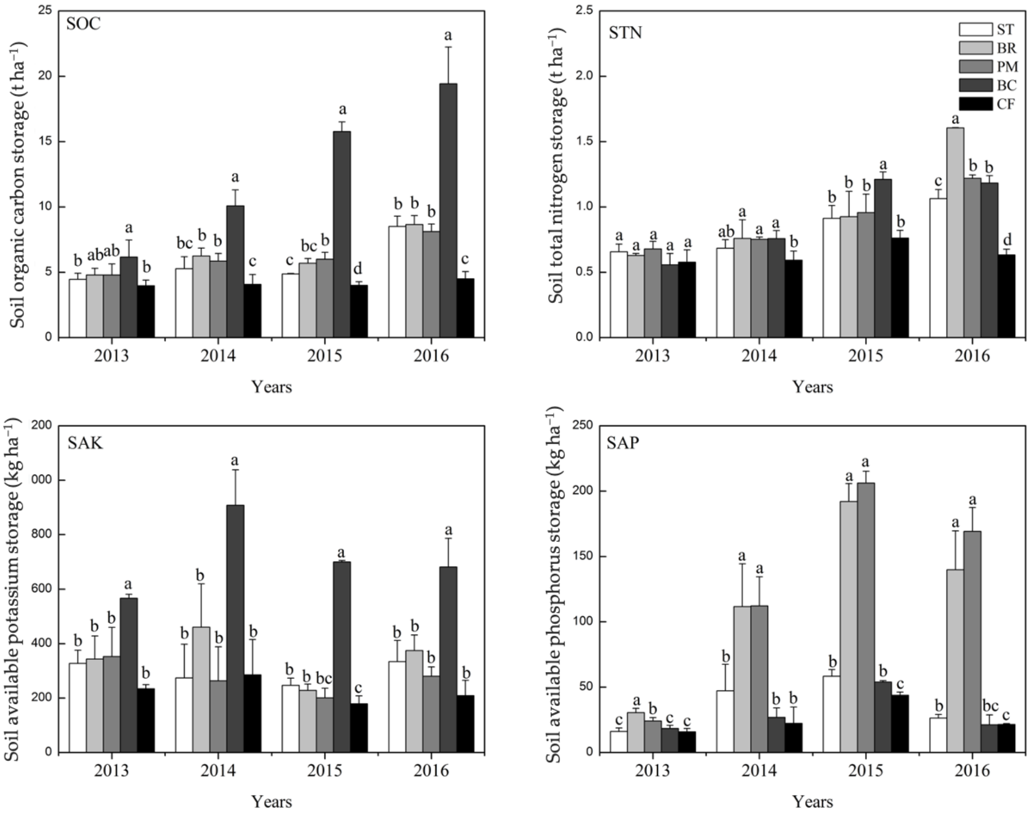

Figure 6. Effect of organic amendment application on soil nutrient storage during a 4-year field experiment. Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

Soil fertility reflects the ability of the soil to provide nutrients for crop growth. The SOC, STN, SAP, and SAK are usually the most important nutrient indicators in crop production and are also important parameters reflecting soil fertility. Multiple comparisons of four soil nutrient data over the past four years showed that the BC treatment had great advantages in improving soil nutrients, with the exclusion of the SAP, followed by the BR and PM treatment. It was found that the addition of OA had a significant effect on improving the nutrient content and productivity in medium- and low-yield farmlands, compared with that of the CF treatment. The contents of SOC and STN increased year by year throughout the experimental years, and the increasing trends were very evident. SAP and SAK also increased, and in general, with the addition of OA and the growth of the experimental years, the soil nutrient status improved, with BC treatment being the most significant, followed by BR and PM.

3.6. Effects of Organic Amendment Application on Yield

Crop yield is affected by soil nutrient status, physical and chemical properties, nutrient release rate in OA, light, heat and water resources, and other factors simultaneously. Moreover, crop yield is a representative index that can be used to directly compare the effects of adding OA. After adding OAs for four consecutive years from 2013 to 2016, the BR and PM treatments increased winter wheat yield by 20.0% and 9.19%, respectively, while the BC and CF treatments decreased winter wheat yield by 19.0% and 6.64%, respectively, compared with that of the ST treatment (Table 3). Due to the phenomena of dead seedlings and early maturity in BC, the yield of wheat decreased after BC treatment. Summer maize yield increased by 6.20% and 6.13% after the BR and PM treatments, respectively, but decreased by 8.12% and 2.62% after the BC and CF treatments, respectively, compared with that of the ST treatment. The same trend as the winter wheat yield was maintained, while the difference between treatments decreased. The effects of OA on yield components of wheat and maize are shown in Tables S2–S5. The BR treatment had the most significant effect on increasing crop yield, followed by PM, while BC and CF treatments reduced crop yield, compared with that of the ST treatment.

Table 3. Effects of organic amendment application on the yield of wheat and maize.

Crops	Treatments	2013 (kg·ha^{-1})	2014 (kg·ha^{-1})	2015 (kg·ha^{-1})	2016 (kg·ha^{-1})	Average (kg·ha^{-1})	Increasing Range %
Winter wheat	ST	–	7963a	7515a	5909c	7129	
	BR	–	9281a	7364a	9018a	8554	20.0%
	PM	–	8931a	7261a	7161b	7784	9.19%
	BC	–	7942a	5042b	4345d	5776	−19.0%
	CF	–	7759a	7229a	4978d	6655	−6.64%
Summer maize	ST	10,232a	12,226a	9926b	9763b	10,537	
	BR	10,490a	13,046a	10,701a	10,525a	11,191	6.20%
	PM	10,660a	12,505a	10,873a	10,694a	11,183	6.13%
	BC	9741a	9220b	9964b	9800b	9681	−8.12%
	CF	10,112a	11,266ab	9913b	9750b	10,260	−2.62%

Note: Values are means (n = 3). Different letters indicate significant differences tested by Duncan's multiple comparison ($p < 0.05$). ST: straw; BR: biogas residue; PM: pig manure; BC: straw biochar; CF: chemical fertilizer.

4. Discussion

4.1. Effects of Organic Amendment Application on Nutrients and Productivity

With the addition of OA and the growth of experimental years, the soil nutrient status improved, with BC treatment as the most significant, followed by BR and PM. For SOCs, the BC treatment had the best effect in the improvement of medium- and low-yield alkaline sandy fields, which was 2.28 times higher than that of the ST control. Meanwhile, the BR, PM, and CF were 1.02, 0.95, and 0.53 times as much as that of the ST control, respectively. Considering the actual situation of C/N and the return amount of OA, the carbon content of ST and BC were twice as much as that of BR and PM. Since the stability and stabilization of BC were greater than that of the other OA treatments, the SOC after BC treatment was much higher than that of the other OA treatments, as SOC play a key role in soil fertility and quality [23,24]. The OA application optimized the soil physicochemical properties and increased Holetta and Robgebeya's SOC by 23–27% and 26–34%, respectively [25]. The results about 4 kinds of OAs application on a low-productivity paddy soil showed that cattle manure and CF were the most efficient OAs in improving C-sequestering, during a 4-year field experiment [26]. The BC-amended soil had significantly greater microaggregate stability, organic C, and total P content [27]. Manure with CF increased grain yield by 6–19%, but greatly increased the SOC content (9–39%) as compared with that of CF, when analyzing the results of 20 long-term field trials and climate change and SOC models to estimate the influence of manure and CF on grain yield [28]. It can be concluded that the application of stabilized OA was particularly significant for the build-up of humus in arable lands and for the land reclamation in organic matter-depleted soils [29]. Therefore, the effect of OA on improving SOC has been widely recognized.

For STNs, the BR treatment had the highest value and was 1.51 times as much as the ST control. Meanwhile, PM, BC, and CF were 1.15, 1.11, and 0.59 times as much as that of the ST, respectively. Since part of the N was supplemented by CF in the field-returning test scheme, there was little retention after CF was applied to the soil, and the difference in TN content between treatments was mainly caused by the difference in N content in the OA. Repeated application of composted materials increases soil organic N content by up to 90%, storing them for mineralization in future planting seasons, usually without leaching nitrate to the groundwater. The OA themselves contain a large number of nitrogen sources, which affect the transformation process of nitrogen and the soil nitrogen content, storing it for mineralization in future cropping seasons, and OA affect the nitrogen absorption of crops [4].

For SAKs, the BC treatment had the highest value and was 2.04 times that of the ST control. Meanwhile, BR, PM, and CF were 1.12, 0.84, and 0.63 times as that of the ST, respectively. The OA application brings potassium source, which releases rapidly and is easily absorbed and used by crops. The SAK content increased and fluctuated within a certain range, which was greatly related to the easy absorption and use of SAK by crops. Compared with ST, the BC treatment significantly increased the SAK content, while BR and PM treatment showed no significant difference. This was consistent with the trend of SAK content in converted amendments, and the key influencing factor of SAK content was clarified. The OA input bring abundant phosphorus source, but also promote the mineralization of phosphorus. The abundant nutrient decomposition in OA enhances the microbial activity and promotes the release of slow-effect phosphorus in the soil. The OA had high P concentrations and provided a high amount of P to plants [30]. For SAPs, PM treatment had the highest value and was 6.44 times that of the ST control. Meanwhile, the BR, BC, and CF were 5.32, 0.81, and 0.82 times that of the ST, respectively. According to other studies, integrating inorganic fertilizers with cattle manure at 4.7 Mg ha^{-1} could effectively improve rice grain yield, SAP, and soil pH [31]. A detailed meta-analysis with 132 long-term ($\geq$10 years) experiments showed that the continuous application of manure significantly increased Olsen P over time [13]. When OA is added to soil, the nutrient status of the soil will be ameliorated, which will then help improve soil productivity [32].

Crop yield is affected by soil nutrient status, physical and chemical properties, nutrient release rate in OA, and climatic factors simultaneously. In the response of OA to crop yield, nutrients may play a larger role than physicochemical soil restoration or amelioration [33]. After adding OA for four consecutive years from 2013 to 2016, the BR and PM treatments increased winter wheat yield by 20.0% and 9.19%, and increased summer maize yield by 6.20% and 6.13%, respectively, as compared with those by the ST treatment. Similarly, BR and PM had homologous results in improving crop productivity. After the application of composted bagasse, farmyard manure, and wheat ST, wheat grain yield increased by 22%, 14%, and 3%, respectively [34]. Yields receiving OA increased by up to 62% on average as compared with that of the controls, throughout all 32 long-term experiments in China [15]. BR and pig slurry as fertilizers resulted in significantly higher wheat yields [35]. A higher grain yield (up to 7.3%) was usually produced in soils with farmyard manure as shown in a 37-year field experiment [14]. It is generally accepted that PM and BR are added to farmland to increase crop productivity [15,28].

4.2. Effect of Biochar Application on Medium- and Low-Yield Alkaline Sandy Farmlands

Although BC treatment had positive effects on SOC content and nutrients, the yield of winter wheat was lower than that of the CF treatment and other OA treatments. The BC treatment itself has good water retention, and more water is absorbed by large BC particles, so less effective water is supplied to crops [36,37]. As a result, when water is insufficient for winter wheat, the root system cannot be tied down, and the early leaves are born slowly; thus, the spike number per hectare will also be reduced in later periods. As the average pH value reached 9.33, whether the excessive pH was the main reason for crop yield reduction after BC application still needs further experiments. The higher the BC application rate, the more obvious the inhibition of winter wheat seedling emergence and seedling growth. The application of BC in alkaline soil inhibits the emergence of wheat when the dose exceeded 3.6% [36]. The application of BC could increase soil conductivity, produce salt pressure, and affect crop water absorption. Similarly, alkaline extracts from BC inhibited the growth of Arabidopsis root hairs [38]. Previous studies have suggested that BC might affect the growth of plant roots through the following mechanisms: (1) the BC reduces the formation of root mycorrhizal fungi by reducing nutrient availability; (2) the BC might alter the signal transduction between mycorrhizae; or mycorrhizal fungi and plants; or microbial activity that had an impact on detoxification [39]. This might be related to the improvement of electrical conductivity and soil pH because of BC application. At the same time, a related study found that high amounts of BC application have no direct economic value for vine growth in soils with poor fertility, alkaline conditions, and temperature [40]. The BC application had no significant effect on the yield of winter wheat and summer maize and the main soil properties (in CEC, in situ soil pH, and SAP) in calcareous sandy-loam soil. Compared with the application in acidic soils, BC application had a limiting effect and reduced its advantages in calcareous soil areas [41].

However, some of the experimental results on BC application were shown to promote crop yield. Using a meta-analysis method, 371 BC-based experiments were selected worldwide to analyze the effects of BC on crop yield and soil properties. The results showed that the effects of BC on soil physicochemical properties ranged from neutral to positive and the yield increased significantly after BC application [37]. In the low-fertility alkaline soil (pH = 8.24), BC (pH = 7.35) significantly increased the biological yield, grain yield, P content, available nitrogen, and SOC and had no negative effect on soil pH and EC [42]. Meanwhile, an experiment was conducted to prove that BC (pH = 10.64 ± 0.01) could be used in calcareous soils (pH = 8.02) without wheat and maize yield loss and significant effects on nutrient availability [43]. These results suggest that BC (pH = 7.4 and 8.4) application to alkaline soils (pH = 7.9) had benefits for both soil quality and lentil growth [44]. Studies also showed that BC (pH = 9.7) combined with fertilizer could be used in slightly alkaline soils (pH = 8.0 and 7.6). The soil fertility parameters of alkaline chernozem improved without significantly increasing the pH value, but the initial pH of BC and soils needed to be taken into account [45]. At present, there is still much controversy about the application of BC in alkaline soils.

Biochar contains a large amount of organic carbon and has useful negative emission potential, which can increase SOC sequestration, increase soil humus, and ultimately affect nutrient cycling and material conversion in soil [37,46,47]. Plant productivity is limited by high pH values in alkaline soils, resulting in low availability of P, Fe, Mg, and sometimes Cu and Zn. The acidic BC is strongly recommended for alkaline soil remediation [48]. High-resolution spectroscopy (micro) and mass spectrometry were used to find organic coating on BC and to explicate its nutrient retention and stimulation of soil fertility [49]. At the same time, some studies also supported the use of alkaline BC in weakly alkaline soils. Therefore, the application of BC in alkaline sandy soils needs further discussion, and it is also necessary to rationally select BC according to different crop growth needs.

4.3. Uncertainty and Limitations

The OA is a huge resource pool that is rich in N and C sources. The addition of exogenous nutrients improves soil fertility in medium- and low-yield farmlands. However, the changes in soil fertility are very complex. On the one hand, it is related to the input of exogenous nutrients; on the other hand, it is also related to crop absorption. In this experiment, the adaptability of alkaline soil was not taken into account in the process of selecting BC. The BC treatment showed significant advantages in improving C sequestration and soil fertility [50,51], but it decreased the yield of winter wheat and summer maize as compared with the ST treatment. Whether the nutrients in the soil can be absorbed by crops is what we are most concerned about, and the most intuitive expression of this is crop growth and crop yield. The carbon in BC after pyrolysis mainly exists in the inert aromatic ring structure, which is a good way to store C and achieve emission reduction, but it is not necessarily absorbed and used by crops. Because the characteristics of different OA vary greatly, the effect of different OA applied to farmland is not the same. Therefore, the collocation of OA should be the focus of future research.

In this study, the PM and BR were better amendments for improved low-fertility sandy alkaline farmlands, and the use of BC requires further research. On the one hand, it is hoped that the factors restricting the growth of winter wheat and summer maize could be found through indoor soil culture, and on the other hand, the types of BC should be changed to search for low pH-BCs that are suitable for alkaline soils. This experiment considered the N and C-based application of agricultural OA comprehensively, and it was innovative and prospective in setting. Currently, the research on the mechanism of the synergistic effect of C and N in the process of agricultural OA returning to the field is still not very clear. We could conduct further in-depth research with the advantage of the experimental setting, hoping to improve the principle support for agricultural OA returning to the field.

5. Conclusions

To address the practical problems of low soil fertility and agricultural OA use in the North China 3H Plain, the ST, PM, BR, and BC were used to carry out a comparative study on crop yield and soil nutrient improvement potential based on a N-based application experiment. Through 4-years-continuous OA application, BR and PM treatment could improve soil nutrient and significantly increase crop yield, which were the better choices to improve medium- and low-yield alkaline sandy farmlands. The BC treatment was the most prominent way to improve soil nutrient status; however, its yield decreased significantly because of high soil pH and other ambiguous reasons. Detailed influences of BC application in alkaline farmlands need further research. The collocation of OA and coordination with fertilizer managements should also be the focus for our future research. Meanwhile, a long-term assessment and detection is needed to identify the most effective and sustainable management measures to improve food production and soil quality in the North China 3H Plain.

Supplementary Materials: The following are available online at https://www.mdpi.com/2073-4395/11/1/157/s1, Table S1: Effect of organic amendment application on soil bulk density (g cm^{-3}) during a 4-year field experiment; Table S2: Effects of organic amendment application on yield components of spike number (106 ha^{-1}), grain number and 1000-grain weight (g); Table S3: Correlation analysis between three factors of yield components and wheat yield; Table S4: Effects of organic amendment application on yield components of number rows per ear, grain number per row and 1000-grain weight(g); Table S5: Correlation analysis between three factors of maize yield and yield components.

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