agriculture

Article

Effects of Combined Application of Chemical Fertilizer and Biochar on Soil Physio-Biochemical Properties and Maize Yield

Jiajun Wu [1,2,†], Liang Jin [1,†], Na Wang [2], Dan Wei [1], Min Pang [2], Dahao Li [3], Junqiang Wang [4], Yan Li [1], Xin Sun [1], Wen Wang [1] and Lei Wang [1,2,*]

1 Institute of Plant Nutrition, Resources and Environment, Beijing Academy of Agricultural and Forestry Sciences, Beijing 100097, China; w1550791604@163.com (J.W.); jinliang19762003@aliyun.com (L.J.); wd2087@163.com (D.W.); li.yan622@163.com (Y.L.); a19963664230@163.com (X.S.); xihanbc202liubang@163.com (W.W.)
2 College of Resources and Environmental Sciences, Agricultural University of Hebei, Baoding 071000, China; wn15512202703@163.com (N.W.); 13716069539@163.com (M.P.)
3 Qiqihar Agricultural Technology Promotion Center, Qiqihar 161000, China; lidahao0452@163.com
4 Qiqihar Branch of Heilongjiang Academy of Agricultural Sciences, Qiqihar 161000, China; august-wjq@163.com
* Correspondence: yzswanglei@163.com
† These authors contributed equally to this work.

Abstract: Excessive, long-term chemical fertilizer application adversely affects soil quality and maize yield. The combined application of biochar with chemical fertilizer can increase maize yield and improve soil fertility. A four-year field experiment was conducted to determine soil physio-biochemical properties and maize yield under a soybean–maize rotation in the black soils of Northeast China. There were five treatments, including no fertilization (CK), fertilizer (NPK), fertilizer + biochar (15.75 t·hm^{-2}, BC$_1$), fertilizer + biochar (31.50 t·hm^{-2}, BC$_2$), and fertilizer + biochar (47.25 t·hm^{-2}, BC$_3$). Compared with CK, the number of macroaggregates and the average weight diameter of soil aggregates in BC$_2$ treatment increased significantly by 10.3% and 24.5%, respectively. The soil pH in the study area was 7.03, and it increased in all treatments except for BC$_1$. The highest pH of 7.17 was recorded in NPK and BC$_2$ treatments, which was around the optimal soil pH. In contrast to the CK and NPK treatments, the biochar application increased soil organic carbon (SOC) and total nitrogen (TN) content. The BC$_2$ treatment improved soil C/N and increased the copy number of soil bacteria by 25.6% compared to CK. The combined application of chemical fertilizer and biochar was better than NPK treatment alone, and improved soil mechanical composition and fine soil particle contents (powder and clay). Mixed biochar with chemical fertilizer application also significantly increased maize yield and the weight of 100 grains increased from 9.5% to 10.9% compared to CK. The maize yield of the three fertilizer and biochar treatments was higher than treatments with applied chemical fertilizer alone, in the order of BC$_2$ > BC$_3$ > BC$_1$ > NPK > CK (BC$_2$ treatment increased by 34.8%). Additionally, the maize yield was significantly and positively correlated with soil aggregates, organic carbon and total nitrogen ($p < 0.05$) as well as the 100-grain weight ($p < 0.01$). The application of 31.50 t·hm^{-2} (BC$_2$ treatment) of biochar can enhance soil physicochemical properties and improve maize yield.

Keywords: soil fertilization; soil amendment; biochar; black soil; Northeast China; yield

check for updates

Citation: Wu, J.; Jin, L.; Wang, N.; Wei, D.; Pang, M.; Li, D.; Wang, J.; Li, Y.; Sun, X.; Wang, W.; et al. Effects of Combined Application of Chemical Fertilizer and Biochar on Soil Physio-Biochemical Properties and Maize Yield. *Agriculture* **2023**, *13*, 1200. https://doi.org/10.3390/agriculture13061200

Academic Editors: Grzegorz Zaguła, Bogdan Saletnik and Marcin Bajcar

Received: 8 May 2023
Revised: 31 May 2023
Accepted: 1 June 2023
Published: 5 June 2023

1. Introduction

In September 2015, world leaders adopted the "2030 Agenda for Sustainable Development" at the United Nations Summit in New York, which covered 17 ambitious global sustainable development goals (SDGs). Out of the 17 SDGs, 13 goals are directly or indirectly related to soil, and soil ecosystem services are bound to provide key guarantees for the achievement of global sustainable development goals [1]. Excessive and long-term applications of chemical fertilizer have led to several environmental problems, such as soil degradation, water eutrophication, nitrogenous gas emissions, etc., thus seriously affecting the sustainability of the agricultural production system [2–5].

The Heilongjiang Province is an important commodity grain base in China, with high natural fertility in black soil. However, in recent years, due to the continuous cultivation of black soil resources and predatory agricultural management, black soil has undergone serious degradation, with weakened water and fertilizer retention capabilities [6]. At the same time, the continuous increase in fertilizer input and the decline in black soil fertility have formed a vicious cycle, turning a portion of high-yield farmland into medium to low-yield farmland, and thus seriously restricting food production and sustainable development in the Northeast region. Evidently, black soil degradation has become a hot topic of concern and an urgent problem to be solved [7,8]. Therefore, black soil restoration and organic fertilization have very important research significance.

Applying organic materials is the best fertilization measure for improving basic soil fertility in black soil farmland. An appropriate amount of organic material will significantly improve nitrogen bioavailability, maize yield, and environmental protection [9,10]. As a major grain-producing area, Northeast China has abundant straw resources, but its recycling and utilization are not ideal. The maize yield in Heilongjiang Province in 2017 was 37.031 million tons. According to the coefficient of grain-to-grass ratio of 1.2, the maize straw yield in that year was 44.437 million tons, while the straw return rate during the same period was only 9.82–45.5%, and burning return rate was 34.3–60.8% [11]. Burning straw in the field is an extreme measure, which not only wastes resources but also pollutes the atmosphere. Research has shown that after maize straw carbonization, the remaining biomass is only one-third of the original straw [12]. As a source of biochar, applying straw charcoal in combination with chemical fertilizers to degraded farmland soil for structural improvement and enhanced fertilizer efficiency increases sinks, reduces emissions, and is a recommended measure to optimize straw resource allocation.

Furthermore, biochar is solid organic matter rich in carbon, and it possesses a high aromatic ring molecular structure and porous characteristics produced by plant biomass pyrolysis under anaerobic or anaerobic artificially-controlled conditions [13]. Due to its irreplaceable advantages, such as large surface area, strong adsorption capacity, high carbon content, good stability, and various nutrients, biochar is widely promoted and used worldwide. Many studies have shown that biochar amendment can significantly increase soil organic carbon, potassium, phosphorus, and calcium content, which improves nutrient cycling, expands nutrient capacity, and reduces nutrient loss, thereby improving soil fertility [14,15]. Additionally, biochar can increase alkali hydrolyzed nitrogen (AN), available phosphorus (AP), available potassium (AK), and microbial content, which collectively improve pH and mechanical composition [16–18]. Therefore, biochar is considered an effective soil conditioner for different soil types [19–21]. Biochar application can also increase the amount of stable carbon and effective nitrogen supply, which is conducive to aggregate formation and soil structure improvement, thereby improving nitrogen utilization efficiency and reducing carbon emissions [22,23]. However, too much biochar input has a negative impact on the antioxidant system, maize seedling growth, and soil fertility [24].

Presently, biochar application research is mainly short-term, performed in greenhouses and laboratories, and focused on tropical and subtropical areas and low fertility soils; however, systematic long-term positioning tests are required for various soils [25]. Research crops mainly include rice–wheat, maize–wheat, rapeseed–rice/maize, rice–leguminous plants, and tomato–wheat–sugar beet–soybean [26–28] rotations. Establishing a reasonable leguminous/non-leguminous plant rotational system is an important way to reduce negative fertilizer input and achieve sustainable agricultural development. Therefore, our aim was to determine the impact of biochar application dosage on soil physicochemical properties and maize yield under a soybean and jade rotation. Our results may significantly guide biochar field applications in typical black soil areas, enhance black soil conservation and efficiency, and assure sustainable food production.

2. Materials and Methods

2.1. Study Area Description

Our experimental site is located at the Modern Park of Minzhu Township, Daowai District, Harbin City, Heilongjiang Province, China (116.3° E, 39.95° N), where elevations range from 300 to 1780 m above sea level. The study site has a humid continental climate, comprising severely dry winters and hot summers. The annual average temperature is 14 °C (−0.58% lower than China's average), and the experimental station typically receives about 109 mm precipitation and 161.37 days of rain annually. The site has a black soil type with a silty loam texture. The basic physical and chemical properties of the soil include a pH = 7, organic matter content = 19.82 g·kg^{-1}, total nitrogen content = 1.33 g·kg^{-1}, available potassium = 183.9 mg·kg^{-1}, and available phosphorus = 19.6 mg·kg^{-1}.

2.2. Experimental Design

We adopted a soybean–maize rotation planting experiment (starting in 2013, while planting soybeans in 2013 and 2015 and planting maize in 2014 and 2016). A total of 5 treatments were set up (Table 1), with different amounts of straw biochar (BC_1, BC_2, and BC_3) applied once.

Table 1. Experiment treatments.

Number	Treatment Content	Fertilization Content
CK	Control treatment	No fertilization
NPK	Fertilizer	Fertilizer dosage: 2013/2015 soybean fertilizer, 2014/2016 maize fertilizer
BC_1	Fertilizer + Biochar1	Fertilizer dosage: Same as NPK Biochar dosage: In 2013, a one-time application of 15.75 t·ha^{-1}
BC_2	Fertilizer + Biochar2	Fertilizer dosage: Same as NPK Biochar dosage: In 2013, a one-time application of 31.50 t ha $^{-1}$
BC_3	Fertilizer + Biochar3	Fertilizer dosage: Same as NPKK Biochar dosage: In 2013, a one-time application of 47.25 t ha $^{-1}$

The fertilization amount for soybeans are as follows: N: Carbamide, 102 kg·ha^{-1}; P: Calcium triple superphosphate, 169 kg·ha^{-1}; K: Potassium sulfate, 66 kg·ha^{-1}. The fertilization amount for maize are as follows: N: Carbamide, 358.7 kg·ha^{-1}; P: Calcium triple superphosphate, 130.4 kg·ha^{-1}; K: Potassium sulfate, 125 kg·ha^{-1}.

Biochar (2.625 t·ha^{-1}) was calculated by multiplying the annual maize straw yield (500 kg·mu^{-1}·year^{-1}) by the Carbon production rate (35%). Biochar 1, 2, and 3 were set as biochar gradient experiments, with application rates of 15.75, 31.50, and 47.25 t·ha^{-1}, respectively. Each treatment was repeated three times, with a community area of 39 m^2 (3.9 m × 10 m).

The spring soybean cultivar was Heinong43, with a planting density of 200,000 plants·ha^{-1}, sown in early May and harvested annually in early October. The spring variety of maize was LonggaoL2, with a planting density of 48,000 plants·ha^{-1}, sown in early May and harvested annually in early October. When sowing, soybean fertilizer was applied once as base fertilizer. For maize cultivation, 1/2 carbamide + total phosphorus and potassium were utilized as the base fertilizers, and the remaining 1/2 carbamide was used in jointing stage topdressing.

Furthermore, biochar was applied in ridges and furrows during sowing. The biochar used in this study was provided by the Liaoning Biochar Engineering Technology Center and made from maize straw pyrolysis (Table 2).

Table 2. Biochar components.

Organic Carbon	Oxygen	Nitrogen	Phosphorus	Potassium	Silicon	Magnesium	Calcium	pH	Particle Composition (%)		
			(g·kg^{-1})						<0.1 mm	0.1–2 mm	>2 mm
598	166	7.85	1.33	17	60	2	3	8.69	15	60.2	24.8

2.3. Methods and Measurements

2.3.1. Sample Collection and Processing

After the maize harvest in October 2021, five sampling points in each plot were randomly selected to collect soil samples in the 0–20 cm soil layer with soil drills. After removing residual plant roots and stones, soil samples were thoroughly mixed, air-dried, and passed through a 10 mm sieve for later analysis.

SOC was determined using the H_2SO_4–$K_2Cr_2O_7$ oxidation method; the total nitrogen was determined using the Kjeldahl method; and the pH was measured using a pHS-3C acidity meter [29]. The grading of aggregates was determined using the wet-sieving method described by Cambardella et al. [30]. The soil mechanical composition was measured using a CLY-2000 laser particle size analyzer. According to the American soil composition grading standard, the soil particles were divided into three grades: sand (2–0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm).

The total soil DNA was extracted from 250 mg of air-dried soil using a DNeasy PowerSoil Pro Kit (Qiagen, Germany) [31].

When the maize was ripe, all maize ears in the community were harvested, and the yield was calculated based on 14% grain moisture content.

2.3.2. Statistical Analysis

Data were statistically analyzed using IBM SPSS Statistics 26. Analysis of variance (ANOVA) was used to determine differences between the control treatment, the treatment with chemical fertilizer alone, and the interaction of biochar with chemical fertilizer on soil physio-biochemical properties and maize yield under soybean–maize rotation. Significant differences were detected at $p < 0.05$ using Duncan's multiple range tests. To investigate the relationships between growth and yield and soil physicochemical properties, we performed a correlation analysis. Simple data processing was performed in Excel, and data was graphically visualized using the Origin 2021 software.

2.3.3. Mean Weight Diameter of Soil Aggregates

The mean weight diameter (MWD) calculation formula [32] is as follows:

$$\mathrm{MWD} = \sum_{i=1}^{n} \bar{x}_i \cdot w_i \quad (1)$$

where n is the number of the aggregate size of classes; d_i is the arithmetic mean of each diameter (mm); and w_i is the weight of ith class.

3. Results

3.1. Effects of Fertilizer and Biochar Application on Soil Aggregate Stability

After four years of soybean–maize rotations, macroaggregates (>0.25 mm) were the dominant aggregates in each single fertilizer application and combined fertilizer and biochar application treatment (Figure 1). Compared with the control (CK) treatment, the experimental treatments NPK, BC_1, BC_2, and BC_3 increased soil aggregates by 4.6, 6.1, 10.3, and 6.6%, respectively. The BC_2 treatment was also significantly different from the NPK treatment. Compared with the CK treatment, the average weight diameter of soil aggregates in the four treatments increased by 10.2, 12.3, 24.5, and 16.9%, respectively, with statistically significant differences for BC_2. Thus, results suggest that biochar application was important for soil aggregates.

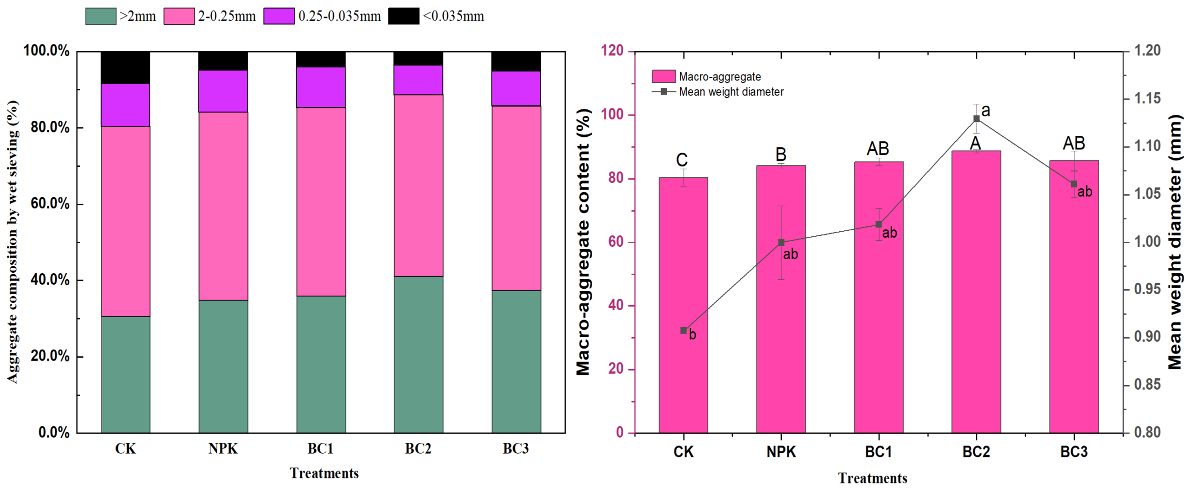

Figure 1. Soil aggregates of different treatments and their average weight diameters. Different uppercase and lowercase letters indicate significant differences at $p < 0.05$. A, B, AB and C represents the difference in Macro-aggregate between different treatments. a, b and ab represents the difference in Mean Weight Diameter between different treatments. Error bars are represented as standard errors.

3.2. Effects of Fertilizer and Biochar Application on Soil Organic Carbon, Total Nitrogen Content, and Carbon–Nitrogen Ratio

The three combined chemical fertilizer and biochar treatments significantly increased soil organic carbon content in the order of $BC_2 > BC_1 > BC_3 >$ NPK > CK. The organic carbon content increment in BC_2 was the highest, increasing by 36.1% compared to CK treatment (Figure 2). For total soil nitrogen, the overall variation pattern was roughly the same as that of organic carbon but differences were also observed. Compared with the CK, the four treatments all increased soil total nitrogen content, with increases from 25.6 to 43.6%. Among them, the NPK, BC_1, and BC_3 treatments had a significant effect compared with the CK and BC_2 treatments. Additionally, except for the BC_2 soil total nitrogen content, the organic carbon and total nitrogen content of the biochar treatments were higher than the normal fertilization treatment, although not significantly different. However, the BC_2 treatment increased soil C/N content and had a significant effect compared to the other three treatments (except for CK), with an increase of 35.2% compared to the NPK treatment. The results showed that the biochar input was critical, compared to non-fertilization and conventional fertilization, in improving soil organic carbon and total nitrogen content and optimizing soil C/N.

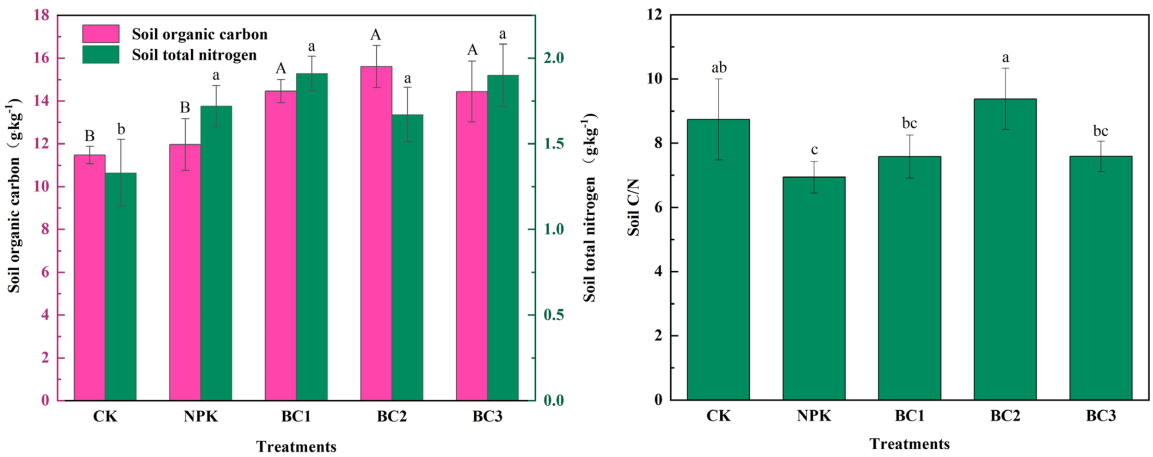

Figure 2. Changes in soil SOC, TN, and C/N ratios under different treatments. Different uppercase and lowercase letters indicate significant differences at $p < 0.05$. In the left figure, A and B represent

the differences in Soil organic carbon between different treatments. a and b represent the difference in Soil total nitrogen between different treatments. In the right figure, a, ab, c and bc represent the difference in Soil C/N among different treatments.

3.3. Effects of Fertilizer and Biochar Application on Soil pH

The soil pH in the study area was 7.03 without fertilization (Figure 3). In addition, except for BC_1, all other treatments significantly increased soil pH, particularly the NPK and BC_2 treatments. The soil pH did not significantly differ between the NPK and BC_2 treatments (7.17 in NPK and 7.16 in BC_2). However, it was within an optimum range. Compared to CK, soil pH in NPK, BC_2, and BC_3 treatments were significantly different. These results indicate that soil pH is influenced by biochar application dosage.

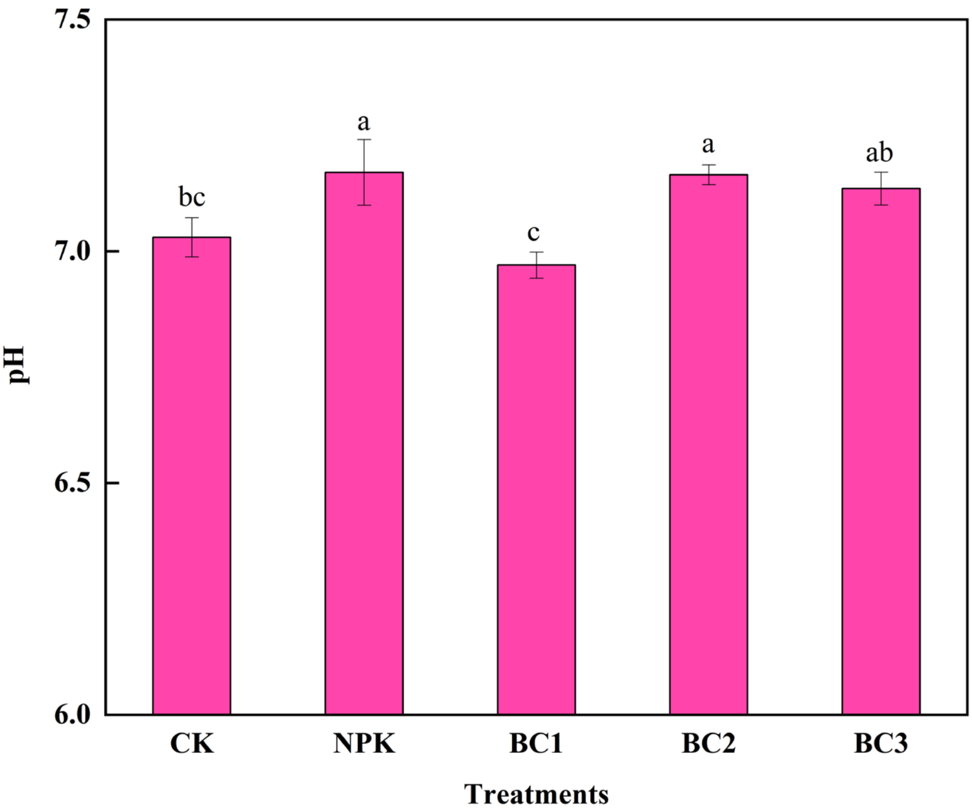

Figure 3. Changes in soil pH with different treatments. a, ab, c and bc represent the significant difference in soil pH among different treatments ($p < 0.05$).

3.4. Effects of Combined Application of Chemical Fertilizer and Biochar on Soil Mechanical Composition

Each treatment of chemical fertilizer alone or combined chemical fertilizer/biochar application changed the soil's mechanical composition (Figure 4). Compared with CK, each treatment reduced sand particle contents, in the order of $BC_2 > BC_3 > BC_1 >$ NPK. Conversely, compared with CK, each treatment increased silt particle contents in the order of $BC_2 > BC_3 > BC_1 >$ NPK. The BC_2 treatment increased silt particles by 19%. Additionally, there was no significant change in clay content between treatments. Compared to CK, the NPK and BC_1 treatments increased clay content, while the BC_2 and BC_3 treatments decreased clay content, with an increasing and decreasing rate of only 1%, respectively.

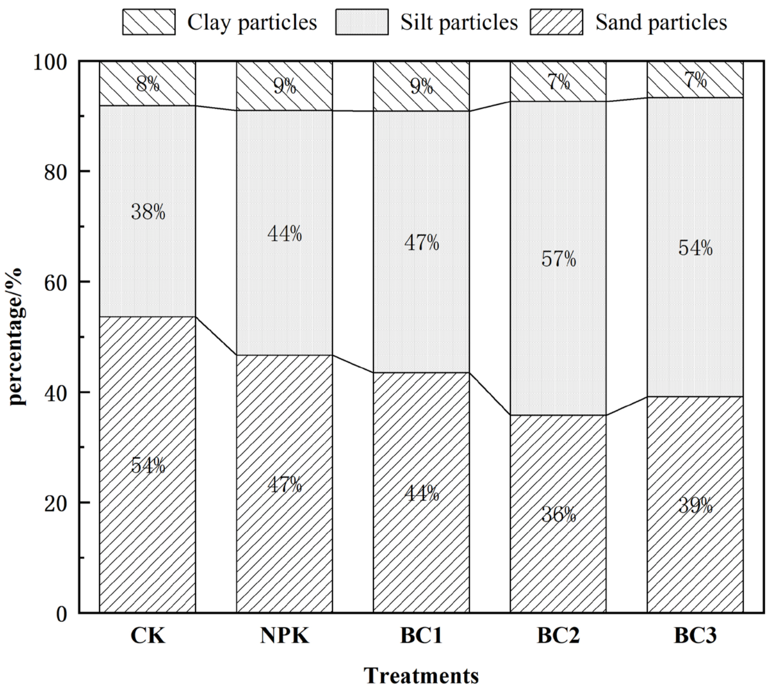

Figure 4. Changes in soil mechanical composition with different treatments.

3.5. Effect of Combined Application of Chemical Fertilizer and Biochar on the Copy Number of 16s rDNA Gene of Soil Bacteria

The 16S rDNA gene copy number in bacteria treated with different biochar treatments was 6.13×10^{10}–8.92×10^{10} copies/g soil (Figure 5). The bacteria treated with BC_2 had the highest copy number of 16S rDNA genes at 8.92×10^{10} copies/g soil, a 25.6% increase compared to the CK treatment, and it was significantly different from other treatments. The second was the BC_3 treatment, which had 8.92×10^{10} copies/g soil, indicating a 21.2% increase over the CK treatment. With minimal NPK processing, there were 6.12×10^{10} copies/g soil, 14.3% less than the CK treatment. Overall, the NPK and BC_1 treatments reduced the 16s rDNA gene copy number, which was significantly different than the CK treatment.

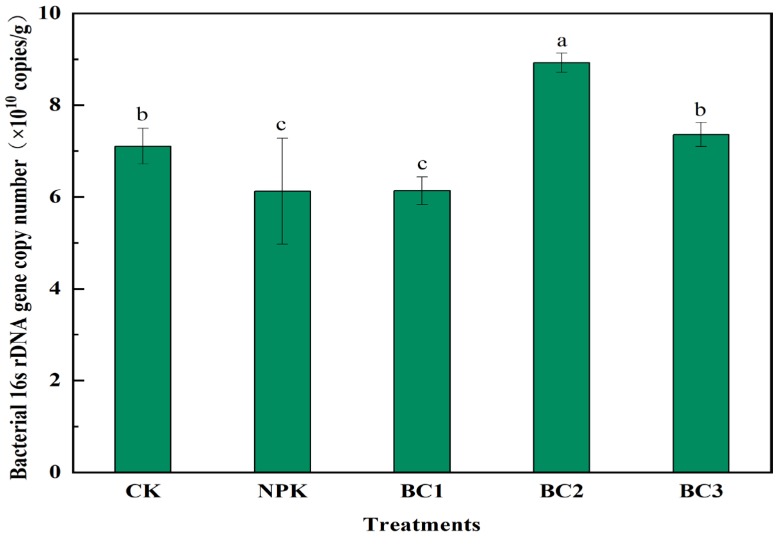

Figure 5. Changes in the number of bacteria 16s rDNA under different treatments. a, b and c represent the significant difference in Bacterial 16s rDNA among different treatments ($p < 0.05$).

3.6. Effects of Fertilizer and Biochar Application on 100-Kernel Weight and Yield of Maize

The combined application of chemical fertilizer and biochar had an important impact on the 100-kernel weight and maize yield (Figure 6). The four fertilizer and biochar application treatments significantly increased the maize's 100-kernel weight and yield. For maize 100-kernel weight, the increase was between 9.5 and 10.9%. Maize yields for the three combined chemical fertilizer and biochar treatments were higher than the NPK treatment applied with only chemical fertilizer, in the order of $BC_2 > BC_3 > BC_1 >$ NPK > CK, with the largest increase of 34.8% observed in the BC_2 treatment.

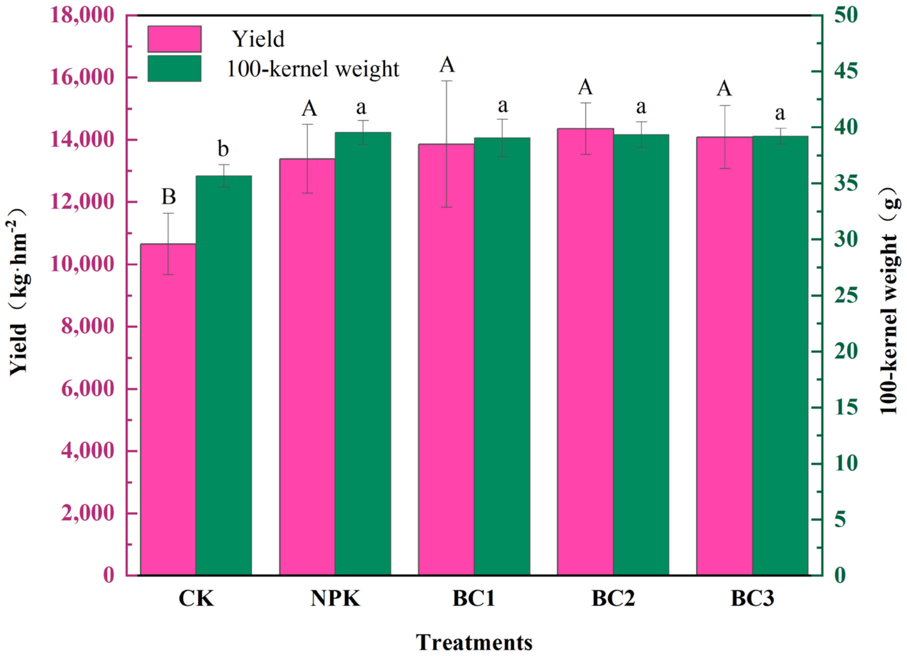

Figure 6. Variation in maize yield and 100-kernel weight of different treatments. Different uppercase and lowercase letters indicate significant differences at $p < 0.05$. A and B represent the difference in maize yield between different treatments. a and b represent the difference in maize 100-kernel Weight between different treatments.

3.7. Correlation Analysis of Soil Physio-Biochemical with Yield and 100-Kernel Weight

The maize yield was significantly and positively correlated with macroaggregates, organic carbon, and total nitrogen ($p < 0.05$), with correlation coefficients of 0.580, 0.549, and 0.528, respectively, and a very significant and positively correlated relationship was also observed with the 100-kernel weight ($p < 0.01$), with a correlation coefficient of 0.769 (Table 3). There was also a significant positive correlation between soil macroaggregates and average weight diameter ($p < 0.01$) and a significant positive correlation between soil macroaggregates and 100-kernel weight and yield ($p < 0.05$). Additionally, there was a significant positive correlation between the average weight diameter of soil macroaggregates and bacterial 16s ($p < 0.05$) and a significant positive correlation between soil organic carbon and total nitrogen ($p < 0.05$). Hence, soil properties are critical for maize growth and yield attributes(Table 4).

Table 3. Correlation analysis of maize yield and soil physicochemical properties and 100-kernel weight.

	Macroaggregates	Mean Weight Diameter	SOC	TN	pH	Bacterial 16s rDNA	100-Kernel Weight	Yield
Macroaggregates	1							
Mean weight diameter	0.714 **	1						

Table 3. *Cont.*

	Macroaggregates	Mean Weight Diameter	SOC	TN	pH	Bacterial 16s rDNA	100-Kernel Weight	Yield
SOC	0.683 **	0.489	1					
TN	0.384	0.330	0.553 *	1				
pH	0.431	0.333	0.058	0.046	1			
Bacterial 16s rDNA	0.447	0.554 *	0.508	−0.177	0.334	1		
100-kernel weight	0.584 *	0.478	0.317	0.512	0.360	−0.117	1	
Yield	0.580 *	0.497	0.549 *	0.528 *	0.134	0.032	0.769 **	1

SOC represents soil organic carbon, TN represents total nitrogen * $p< 0.05$, ** $p< 0.01$.

Table 4. Partial correlation analysis of maize yield and soil physio-biochemical and 100-kernel weight.

	Macroaggregates	Mean Weight Diameter	SOC	TN	pH	Bacterial 16s rDNA	100-Kernel Weight
Correlation	0.276	0.188	0.165	0.225	−0.104	−0.326	0.661
Significance (two-tail)	0.340	0.519	0.574	0.439	0.722	0.255	0

4. Discussion

The soil aggregate content and stability play an important role in soil water, fertilizer retention capacity, and soil bacterial activity. Soil aggregates are the basic unit of soil structure. It is generally believed that the higher the soil macroaggregates (>0.25 mm) content, the more stable the soil structure [33]. In this study, different biochar doses in the BC_1, BC_3 and BC_3 treatments altered soil structure compared to non-biochar treatments. Furthermore, the soil macroaggregates significantly increased in the BC_2 treatment (application of 31.5 t·hm^{-2} biochar). This further indicates that the combined application of chemical fertilizer and biochar is more conducive to soil macroaggregates formation and could be due to the biochar's porous structure and large specific surface area. Biochar is a good soil binder and promotes macroaggregates formation [34]. However, as the amount of biochar application increased, the number of soil macroaggregates tended to decrease, which is consistent with the research results of Wang et al. [35]. When the amount of biochar applied was very high, the soil macroaggregate content significantly decreased.

The average weight diameter (MWD) of soil aggregates is often used as an important indicator of soil aggregate stability and is closely related to soil erosion resistance. The higher the MWD, the higher the soil macroaggregate content and the stronger the soil structural stability and erosion resistance [32]. In this study, compared to CK, all treatments containing biochar increased the average weight diameter of soil aggregates, as previously reported by Yang et al. [36].

Soil organic carbon is an important soil aggregate component, and biochar application increases its soil content. In addition, soil total nitrogen is a key element for plant growth and development, and its concentration has an important influence on the soil fertility index [37]. Some scholars have conducted research on the effect of biochar on topsoil (0–10 cm) and found that it can increase macroaggregates, thereby improving soil structural stability and soil organic carbon [38]. Meanwhile, other studies have revealed that biochar application directly increases soil organic carbon [39]. In this study, low to high biochar doses increased soil organic carbon content compared to non-fertilization and single fertilizer treatments. The increase in organic carbon was largely influenced by direct input from biochar. Conversely, biochar application enhanced soil organic carbon stability and reduced organic carbon decomposition [40]. Our results also indicate that biochar application affected soil total nitrogen content to varying degrees, which is similar to the results of Zhang et al. and Zhu et al. [41,42].

Previous studies have shown that biochar's impact on soil pH mainly stems from the biochar's pH and its nitrification [43] but also depends on the soil properties to which the biochar is applied, ultimately increasing or decreasing soil pH. For example, Jiang et al. [44]

found that the application of tobacco straw biochar in acidic soil significantly increased the soil pH. Furthermore, Wang et al. [45] studied biochar's effects on alkaline soil and found that the pH of the local soil decreased significantly. In this study, all treatments except BC_1 changed the soil pH to varying levels. Medium and high biochar doses in BC_2 and BC_3 treatments, respectively, increased soil pH, probably because the pH of the biochar used in this experiment was higher than the pH value of the soil itself, so when a large amount of biochar was applied, the soil pH rose accordingly.

Soil mechanical composition is one of the most important soil physical properties, and the quantity and quality of fine soil particles (silt and clay) reflect soil nutrient content and soil fertility retention [46]. We showed that different additional amounts of biochar improved soil mechanical composition, reduced sand content, and increased the proportion of particles. These observations occur because biochar itself has a large specific surface area and high adsorption, so it can combine with small soil particles, forming a larger aggregate structure, thereby improving soil structure [47]. These results are consistent with the research results of Tang et al. [48], who studied an aeolian sandy soil area in northwest Liaoning and found that different amounts of biochar could improve the soil's mechanical composition and increase the proportion of silt particles.

The improvement of the soil's physical and chemical properties by biochar also increased the number of bacteria, which is consistent with the research results of Hu et al. [49]. In our study, the BC_2 and BC_3 treatments increased the number of bacteria in the soil to varying degrees because the relatively large specific biochar surface area provided suitable living spaces for them. It is rich in nutrients, which are necessary for the growth of microorganisms, such as bacteria; however, the number of bacteria treated with BC_1 decreased somewhat, which may be due to the decrease in soil pH resulting in a less ideal microbial growth environment.

Many studies have described the potential impact of soil biochar addition on maize growth [50]. Due to possible changes in soil quality, biochar addition improves plant growth by directly affecting root development while also changing soil fertilizer retention capacity. However, if too much biochar is added, it will have a negative impact on maize growth [51]. Our results are consistent with previous studies. Biochar application significantly increased the maize's 100-kernel weight and yield. However, with increasing biochar application, the 100-kernel weight did not significantly change but the yield was somewhat reduced. The correlation analysis between maize yield and soil characteristics showed significant positive correlations between maize yield and soil macroaggregates, organic carbon, and total nitrogen content, and a very significant positive correlation between maize yield and 100-kernel weight. These factors are closely related to biochar input. Compared to the soil without biochar, biochar-rich soil provides more favorable nutrients for maize growth, such as organic carbon and total nitrogen [52]. It also improves soil aggregate structure, thereby promoting maize growth and increasing yield.

5. Conclusions

Our results indicate that the application of both NPK and relatively large amounts of biological carbon can significantly increase soil pH and maintain it in the optimal range. In the presence of biochar, soil fine particle contents, the number of soil macroaggregates, and their MWD increases, leading to an increase in the soil organic carbon content. Compared with the CK treatment, all treatments significantly increased soil nitrogen content and increased maize yield. Additionally, the increase in soil macroaggregates, organic carbon, and total nitrogen content improved maize yield.

Based on experimental results, the application of 31.50 $t \cdot hm^{-2}$ could be an optimum biochar dose for soil physical and chemical properties and maize yield in typical black soil areas. However, maize yield and soil characteristics are also constrained by multiple factors, such as humus content and farming practices. As the number of years of biochar application increases, the biochar amendment could provide different results; therefore, it is necessary to investigate the long-term impacts of different biochar application dosages on soil physical and chemical properties and maize yield.

Author Contributions: Conceptualization, J.W. (Jiajun Wu); methodology, L.J. and L.W.; resources, D.W. and L.J.; software, M.P., D.L. and J.W. (Junqiang Wang); supervision, Y.L.; visualization, J.W. (Jiajun Wu); writing—original draft, J.W. (Jiajun Wu), L.J. and N.W.; writing—review and editing, J.W. (Jiajun Wu), N.W., D.W., M, P., D, L., J.W. (Junqiang Wang), Y.L., X.S., W.W., L.J. and L.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Capacity Improvement Project of Beijing Academy of Agricultural and Forestry Sciences (ZHS202304), the National Key R&D Plan (2022YFD1500200-1), the Technological Innovation for the Protection and Utilization of Black Land (XDA28130200), the Beijing Academy of Agricultural and Forestry Sciences Youth Fund (QNJJ202214), the general program of NSFC (41977095), the Beijing Postdoctoral Fund, the Postdoctoral Research Fund of Beijing Academy of Agricultural and Forestry Sciences (2020-ZZ-026), Beijing Academic Program (Artificial sponge soil construction and its water regulation mechanism).

Data Availability Statement: Not applicable.

Acknowledgments: We appreciate and thank the anonymous reviewers for their helpful comments that led to an overall improvement of the manuscript. We also thank the Journal Editor Board for their help and patience throughout the review process. Finally, we thank Shah Jahan Leghari for editing the English of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lal, R.; Bouma, J.; Brevik, E.; Dawson, L.; Field, D.J.; Glaser, B.; Zhang, J. Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective. *Geoderma Reg.* **2021**, *25*, e00398. [CrossRef]
2. Islam, M.S.; Bell, R.W.; Miah, M.M.; Alam, M.J. Farmers' fertilizer use gaps relative to government recommendations in the saline coastal zone of the Ganges Delta. *Agron. Sustain. Dev.* **2022**, *42*, 59. [CrossRef] [PubMed]
3. Hui, K.; Xi, B.; Tan, W.; Song, Q. Long-term application of nitrogen fertilizer alters the properties of dissolved soil organic matter and increases the accumulation of polycyclic aromatic hydrocarbons. *Environ. Res.* **2022**, *215*, 114267. [CrossRef] [PubMed]
4. Bai, Y.C.; Chang, Y.Y.; Hussain, M.; Lu, B.; Zhang, J.P.; Song, X.B.; Pei, D. Soil chemical and microbiological properties are changed by long-term chemical fertilizers that limit ecosystem functioning. *Microorganisms* **2020**, *8*, 694. [CrossRef] [PubMed]
5. Qin, X.; Guo, S.; Zhai, L.; Pan, J.; Khoshnevisan, B.; Wu, S.; Liu, H. How long-term excessive manure application affects soil phosphorous species and risk of phosphorous loss in fluvo-aquic soil. *Environ. Pollut.* **2020**, *266*, 115304. [CrossRef]
6. Gu, Z.; Xie, Y.; Gao, Y.; Ren, X.; Cheng, C.; Wang, S. Quantitative assessment of soil productivity and predicted impacts of water erosion in the black soil region of northeastern China. *Sci. Total Environ.* **2018**, *637*, 706–716. [CrossRef]
7. Zhao, P.; Li, S.; Wang, E.; Chen, X.; Deng, J.; Zhao, Y. Tillage erosion and its effect on spatial variations of soil organic carbon in the black soil region of China. *Soil Tillage Res.* **2018**, *178*, 72–81. [CrossRef]
8. Chen, D.; Wang, C.; Shen, J.; Li, Y.; Wu, J. Response of CH_4 emissions to straw and biochar applications in double-rice cropping systems: Insights from observations and modeling. *Environ. Pollut.* **2018**, *235*, 95–103. [CrossRef]
9. Wei, Y.; Shi, G.; Wu, Y.; Liu, H. Effects of biochar application models and land productivity evaluation on sloping farmland in black soil areas. *J. Agric. Mach.* **2018**, *11*, 251–259. [CrossRef]
10. Hu, X.; Liu, J.; Zhu, P.; Wei, D.; Jin, J.; Liu, X.; Wang, G. Long-term manure addition reduces diversity and changes community structure of diazotrophs in a neutral black soil of northeast China. *J. Soils Sediments* **2018**, *18*, 2053–2062. [CrossRef]
11. Liu, X.; Li, S. The spatiotemporal distribution characteristics of straw nutrient resources and return to farmland in China. *J. Agric. Eng.* **2017**, *21*, 1–19. [CrossRef]
12. Meng, J.; Zhang, W.; Wang, S.; Xu, Z.; Chen, W. Development and Prospects of the Technology of Agricultural and Forestry Waste Carbonization and Returning to the Field. *J. Shenyang Agric. Univ.* **2011**, *4*, 387–392. [CrossRef]
13. Lehmann, J.; Joseph, S. *Biochar for Environmental Management: Science, Technology and Implementation*; Routledge: London, UK, 2015.
14. Zhao, H.; Jiang, Y.; Ning, P.; Liu, J.; Zheng, W.; Tian, X.; Shar, A.G. Effect of different straw return modes on soil bacterial community, enzyme activities and organic carbon fractions. *Soil Sci. Soc. Am. J.* **2019**, *83*, 638–648. [CrossRef]
15. Lu, W.L.; Dong, J.W.; Song, W.J.; Liu, K.L.; Zhang, Q.M.; Zhang, H.W.; Liang, H.B. Effects of deep soil tillage and straw returning on soil physical properties and yield and quality of tobacco leaves Chin. *Tob. Sci.* **2019**, *40*, 25–32.
16. Arif, M.; Ali, K.; Jan, M.T.; Shah, Z.; Jones, D.L.; Quilliam, R.S. Integration of biochar with animal manure and nitrogen for improving maize yields and soil properties in calcareous semi-arid agroecosystems. *Field Crops Res.* **2016**, *195*, 28–35. [CrossRef]
17. Hu, F.; Xu, C.; Ma, R.; Tu, K.; Yang, J.; Zhao, S.; Zhang, F. Biochar application driven change in soil internal forces improves aggregate stability: Based on a two-year field study. *Geoderma* **2021**, *403*, 115276. [CrossRef]

18. Tan, Z.; Lin, C.S.; Ji, X.; Rainey, T.J. Returning biochar to fields: A review. *Appl. Soil Ecol.* **2017**, *116*, 1–11. [CrossRef]
19. Laird, D.; Fleming, P.; Wang, B.; Horton, R.; Karlen, D. Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma* **2010**, *158*, 436–442. [CrossRef]
20. Pokharel, P.; Ma, Z.; Chang, S.X. Biochar increases soil microbial biomass with changes in extra-and intracellular enzyme activities: A global meta-analysis. *Biochar* **2020**, *2*, 65–79. [CrossRef]
21. Sachdeva, V.; Hussain, N.; Husk, B.R.; Whalen, J.K. Biochar-induced soil stability influences phosphorus retention in a temperate agricultural soil. *Geoderma* **2019**, *351*, 71–75. [CrossRef]
22. Wei, Y.; Shi, G.; Feng, C.; Wu, Y.; Liu, H. Effects of biochar application on soil structure and soybean yield in sloping farmland of black soil area. *J. Agric. Mach.* **2019**, *8*, 309–320. [CrossRef]
23. Ji, C.; Li, S.; Geng, Y.; Miao, Y.; Ding, Y.; Liu, S.; Zou, J. Differential responses of soil N_2O to biochar depend on the predominant microbial pathway. *Appl. Soil Ecol.* **2020**, *145*, 103348. [CrossRef]
24. Zhang, C.; Zeng, G.; Huang, D.; Lai, C.; Chen, M.; Cheng, M.; Wang, R. Biochar for environmental management: Mitigating greenhouse gas emissions, contaminant treatment, and potential negative impacts. *Chem. Eng. J.* **2019**, *373*, 902–922. [CrossRef]
25. Egene, C.E.; Van Poucke, R.; Ok, Y.S.; Meers, E.; Tack, F. Biochar for the long-term stabilization of metals in low to moderately contaminated soils. In Proceedings of the 4th International Conference on Contaminated Land, Ecological Assessment and Remediation, HongKong, China, 16–18 August 2018; Hong Kong Polytech University: Hong Kong, China, 2018; p. 226.
26. Singh, V.K.; Sharma, B.B.; Dwivedi, B.S. The impact of diversification of a rice–wheat cropping system on crop productivity and soil fertility. *J. Agric. Sci.* **2002**, *139*, 405–412. [CrossRef]
27. N'Dayegamiye, A.; Whalen, J.K.; Tremblay, G.; Nyiraneza, J.; Grenier, M.; Drapeau, A.; Bipfubusa, M. The benefits of legume crops on corn and wheat yield, nitrogen nutrition, and soil properties improvement. *Agron. J.* **2015**, *107*, 1653–1665. [CrossRef]
28. Gagnon, B.; Pouleur, S.; Lafond, J.; Parent, G.; Pageau, D. Agronomic and economic benefits of rotating corn with soybean and spring wheat under different tillage in eastern Canada. *Agron. J.* **2019**, *111*, 3109–3118. [CrossRef]
29. Bao, S. *Soil Agrochemical Analysis Beijing*; China Agricultural Publishing House: Beijing, China, 2005; pp. 23–107.
30. Cambardella, C.A.; Elliott, E.T. Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Sci. Soc. Am. J.* **1993**, *57*, 1071–1076. [CrossRef]
31. Maretto, L.; Deb, S.; Ravi, S.; Chiodi, C.; Manfredi, P.; Squartini, A.; Stevanato, P. Microbial Diversity of Reconstituted, Degraded, and Agricultural Soils Assessed by 16S rDNA Multi-Amplicon Sequencing. *Front. Environ. Sci.* **2022**, *9*, 690. [CrossRef]
32. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; American Society of Agronomy, Inc.: Fitchburg, WI, USA, 1986; Volume 5, pp. 425–442. [CrossRef]
33. Yan, Y.; Cheng-Hua, L.; Zhong-Jian, P. Effect of greenhouse soil management on soil aggregation and organic matter in northeast china. *Catena* **2015**, *133*, 412–419. [CrossRef]
34. Wang, X.; Xie, Z.; Dong, H.; Zhao, Y.; Liu, H.; Lou, C. The effect of returning straw to the field on maize yield, soil aggregate composition, and organic carbon distribution. *Corn Sci.* **2018**, *1*, 108–115. [CrossRef]
35. Wang, Y.; Niu, W.; Li, X.; Wang, J.; Guan, Y.; Dong, J. Effect of biochar on soil aggregate structure in sunlight greenhouse. *Soil Water Conserv. Bull.* **2019**, *4*, 190–195. [CrossRef]
36. Yang, W.; Hui, C.; Chen, Y.X.; Song, S.L.; Yang, M.; Guo, S. Stability and classification characteristics of soil aggregates in irrigated farmland under the application of biomass charcoal. *J. Soil Water Conserv.* **2022**, *6*, 323–329. [CrossRef]
37. Zhang, W.M.; Chen, W.F.; Meng, J.; Jin, L.; Guo, W.; Zhao, H.L. Research on the Utilization Potential, Industrial Model, and Development Strategy of Straw Biochar in Northeast China. *Chin. Agric. Sci.* **2019**, *14*, 2406–2424. [CrossRef]
38. Zhang, Q.; Du, Z.L.; Lou, Y.; He, X. A one-year short-term biochar application improved carbon accumulation in large macroaggregate fractions. *Catena* **2015**, *127*, 26–31. [CrossRef]
39. Dong, X.; Singh, B.P.; Li, G.; Lin, Q.; Zhao, X. Biochar application constrained native soil organic carbon accumulation from wheat residue inputs in a long-term wheat-maize cropping system. *Soil Tillage Res.* **2018**, *252*, 200–207. [CrossRef]
40. Han, L.F.; Sun, K.; Yang, Y.; Xia, X.H.; Li, F.B.; Yang, Z.F.; Xing, B.S. Biochar's stability and effect on the content, composition and turnover of soil organic carbon. *Geoderma Int. J. Soil Sci.* **2020**, *364*, 114184. [CrossRef]
41. Zhang, Y.S.; Tang, G.G.; Long, X.S.; Ge, C.H.; Xu, W.L. Effects of one-time application of biochar on soil properties and corn yield in irrigated sandy soil. *Agric. Res. Arid. Areas* **2021**, *4*, 137–141. [CrossRef]
42. Zhu, H.Y.; Gao, M.; Long, Y.; Xu, G.X.; Wang, F.H.; Wang, Z.F. The effect of reduced fertilizer and organic substitution on nitrogen and phosphorus nutrients in purple soil and crop yield in arid sloping fields. *Environ. Sci.* **2020**, *4*, 1921–1929. [CrossRef]
43. Dai, Z.; Wang, Y.; Muhammad, N.; Yu, X.; Brookes, P.C. The effects and mechanisms of soil acidity changes, following incorporation of biochars in three soils differing in initial ph. *Soil Sci. Soc. Am. J.* **2014**, *78*, 1606. [CrossRef]
44. Jiang, C.; Zu, C.; Wang, H.; Yan, Y.; Liu, Y.; Shen, J. Straw Return with Biochar Increased Soil Macro-Aggregates and Improved Flue-Cured Tobacco (*Nicotiana tabacum* L.) Yield and Quality. *Appl. Ecol. Environ. Res.* **2022**, *20*, 207–219. [CrossRef]
45. Wang, X.F.; Li, Y.; Yao, N.; Liu, H.G.; Fan, X.Y.; Zhang, X. Analysis of Soil Physical and Chemical Properties and Salt Effects of Cotton Beet Intercropping Improved by Biochar. *J. Agric. Mach.* **2022**, *4*, 352–362. [CrossRef]
46. Lv, W.Q.; Dang, H.Z.; Wang, L.; Dang, H.J.; He, X.D. Spatial differentiation characteristics of soil physicochemical properties of zonal vegetation on the Loess Plateau. *J. Grassl. Ind.* **2016**, *10*, 21–30. [CrossRef]
47. Fu, Q.; Zhao, H.; Li, T.; Hou, R.; Liu, D.; Ji, Y.; Yang, L. Effects of biochar addition on soil hydraulic properties before and after freezing-thawing. *Catena* **2019**, *176*, 112–124. [CrossRef]

48. Tang, J.X.; Li, Y.; Zhu, Y.L.; Xiang, B.; Tan, T. Study on the Effects of Biochar and Bentonite on the Physical and Chemical Properties of Aeolian Sandy Soil in Northwest Liaoning. *Resour. Environ. Arid. Areas* **2022**, *3*, 143–150. [CrossRef]
49. Hu, H.Y.; Zhang, H.; Cao, S.; Yin, D.Y.; Zhou, C.F.; He, Z.M. Effects of biochar application in soil of Chinese fir plantations on bacterial community structure and diversity. *For. Sci.* **2019**, *8*, 184–193. [CrossRef]
50. Dong, L.; Wang, J.; Shen, M.; Zhang, H.; Wang, L.; Li, C.; Lu, C. Biochar combined with nitrogen fertilizer affects soil properties and wheat yield in medium-low-yield farmland. *Soil Use Manag.* **2022**, *38*, 584–595. [CrossRef]
51. Chen, B.; Zhou, D.; Zhu, L. Transitional adsorption and partition of nonpolar and polar aromatic contaminants by biochars of pine needles with different pyrolytic temperatures. *Environ. Sci. Technol.* **2008**, *42*, 5137–5143. [CrossRef]
52. El-Naggar, A.; Lee, S.S.; Rinklebe, J.; Farooq, M.; Song, H.; Sarmah, A.K.; Ok, Y.S. Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma* **2019**, *337*, 536–554. [CrossRef]