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Biochar-Based Fertilizer Improved Crop Yields and N Utilization Efficiency in a Maize–Chinese Cabbage Rotation System

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Abstract: Optimizing fertilization strategies is crucial for obtaining high crop yields and efficient N utilization. This study aimed to understand the potential increase in crop yield and the N utilization efficiency under biochar-based fertilizer (BF) in a maize–Chinese cabbage rotation system. Biochar-based slow-release fertilizer (BF) is an important nutrient-efficient management strategy. The yields and growth-related traits of the crops, N utilization efficiency, quality, and dynamic changes in soil inorganic N in a maize-cabbage rotation system were investigated in a pot experiment under three N fertilizer application strategies in 2019–2020; the maize stage included (1) zero-N fertilizer, i.e., control (N 0 g pot^{-1}); (2) NPK (N 5.25 g pot^{-1}); and (3) BF (N 5.25 g pot^{-1}). The Chinese cabbage stage included (1) zero-N fertilizer, i.e., control (N 0 g pot^{-1}); (2) NPK (N 6.25 g pot^{-1}); and (3) BF (N 6.25 g pot^{-1}). Compared with the CK and NPK treatments, the BF treatment had the highest average maize and Chinese cabbage yields at 86.99 g plant^{-1} and 498.88 g plant^{-1}, respectively. BF improved the plant height, stem diameter, and ear height of maize and the leaf length, leaf width, and leaf number of Chinese cabbage, as well as increased the N utilization efficiency of maize and cabbage. BF increased the starch content of maize grain and the amino acid, sugar, and vitamin C contents of cabbage. In the critical growth stages of maize and Chinese cabbage, BF application increased the content of soil inorganic N, which coincided with the nutrient requirements in the critical growth stages of the crops. Overall, BF is an effective method to improve crop yield and N utilization in the maize–Chinese cabbage rotation systems and is a fertilization strategy with broad applicability prospects.

Keywords: biochar; maize–cabbage system; yield; crop quality; N utilization efficiency; soil inorganic N

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Citation: Zhao, H.; Xie, T.; Xiao, H.; Gao, M. Biochar-Based Fertilizer Improved Crop Yields and N Utilization Efficiency in a Maize–Chinese Cabbage Rotation System. *Agriculture* **2022**, *12*, 1030. https://doi.org/10.3390/agriculture12071030

Academic Editors: Chengfang Li and Lijin Guo

Received: 14 June 2022
Accepted: 13 July 2022
Published: 14 July 2022

1. Introduction

Along with the growth of the world's population, global food demands are on the rise [1], with the expectation that per capita food requirements will nearly double by 2050 [2]; however, there is increasing concern over the mounting burden of food production [3]. In response to these challenges, it is evident that an increase in crop yield per acre is vital. The most consumed crop nutrient is nitrogen (N) [4], and N fertilization is an important agricultural technology to increase crop production per unit of land, which is important for economic and social progress [5]. Unfortunately, the amount of conventional N fertilizer used in agricultural production is increasing while plant N fertilization efficiency is underperforming, and crop yield potential is not realized [6,7]. The type and quantity of fertilizer affects not only crop yields but also soil physicochemical properties, which in turn have a significant effect on soil fertility and productivity [8,9]. Because of leaching, volatilization, denitrification, fixation, erosion, and runoff, there will be inefficiencies in crop nutrient use and environmental pollution, in addition to increases in fertilizer prices, with negative economic and environmental impacts [3,10–12]. Therefore, a balanced strategy is required to maintain crop yield and N utilization efficiency while also minimizing nutrient losses during crop production.

In modern agricultural production, the application of slow-release fertilizers (SRFs) is vital technology to ensure that crops are produced in a sustainable and high-quality manner [13,14]. Nevertheless, SRFs are extremely expensive, so they are not used widely. Biochar-based slow-release fertilizers can solve the nutrient deficiencies of biochar, the high nutrient loss rate of traditional chemical fertilizers, and low crop nutrient utilization [15,16], primarily due to the benefits of biochar nutrient retention, carbon sequestration, emission reduction, and soil improvement, while realizing the functions of nutrient adsorption and slow-release, reducing nutrient loss [17,18]. As a result of their wide availability and extreme cost-effectiveness across the globe, biochar-based resources can be used as cost-effective and climate-smart nutrient carriers for the formulation of slow-release fertilizers [19]. Biochar-based slow-release fertilizers (BFs) are a new type of fertilizer derived from combining biochar and chemical fertilizers through a specific process [20]. According to research, BFs can reduce the number of chemical fertilizers and application times, improve crop nutrient efficiency, increase crop yield and quality, and improve soil physical and chemical properties, which allow for improvements in the utilization rate of agricultural waste [21,22]. It is becoming increasingly popular to use biochar-based slow-release fertilizers in agriculture due to their high fertilizer efficiency and low environmental impact [3].

Crop rotation is one of the most effective ways to maximize agricultural economic benefits and productivity per unit of arable area, but different crop rotation systems, soil types, and fertilizer levels affect crop yield differently [23–25]. Waxy maize, also called sticky maize, can be processed or consumed directly, and its value is high, economically, nutritionally, and processing wise [26]. Vegetables are of great economic importance, and their cultivation continues to increase [27]. The rotation of maize and vegetables is a widespread practice in Southwest China [12]. Crop rotation systems positively impact land-use efficiency and crop yield. Nevertheless, inadequate nutrient uptake by plants and environmental effects caused by unreasonable N fertilization are common problems. There have been few reports of biochar-based slow-release fertilizers in the yellow soil maize-cabbage rotation system in Guizhou, China.

Here, we performed a two-year study (2019–2020) using pot experiments focusing on the effect of biochar-based fertilizers on a maize–Chinese cabbage rotation system. However, there is little information available on BF application for crop yield and changes in soil inorganic N dynamics, particularly in yellow soil under maize–vegetable (Chinese cabbage) rotation systems. Therefore, we aimed to (1) investigate the effects of BF application on maize-cabbage yields and biological traits; (2) determine maize-cabbage N uptake and utilization efficiency under BF application; and (3) clarify the effects of BF application on the maize–Chinese cabbage rotation system and the dynamic changes in soil NH_4^+-N and NO_3^--N.

2. Materials and Methods

2.1. Site Description

Pot experiments were conducted at the Institute of Soil Fertilization, Guizhou Academy of Agricultural Sciences (1060 m above sea level, 106°07′ E, 26°11′ N), Guizhou, China. The pot experiment took place from 2019 to 2020. The area has a subtropical monsoon climate, with an average annual temperature of 15.3 °C and yearly rainfall of 1100–1200 mm. Before the experiment, the soil chemistry was determined; the pH was 7.29, and the SOM content was 25.24 g kg^{-1}. The available nitrogen (N, alkaline hydrolysis N), phosphorus (P, Olsen-

P), and potassium (K, ammonium acetate-extractable K) contents were 78.40, 9.85, and 85.76 mg kg^{-1}, respectively.

2.2. Experimental Design

The experiment consisted of three treatments, and each treatment was repeated three times, according to a completely random design. The diameter and height of each plastic pot were 38 cm and 40.5 cm, respectively. Each pot was filled with 25 kg of soil. The soil samples were collected locally from 0 to 20 cm in a field experiment at the Institute for Soil Fertilization, Guizhou Academy of Agricultural Sciences. The soil was typic yellow soil (entisol); one maize or one cabbage plant was planted per pot. The experimental treatments in the annual maize stage included (1) zero-N fertilizer, i.e., control (N 0 g pot^{-1}, P_2O_5 2.75 g pot^{-1}, and K_2O 5.25 g pot^{-1}); (2) NPK (N 5.25 g pot^{-1}, P_2O_5 2.75 g pot^{-1}, and K_2O 5.25 g pot^{-1}); and (3) BF (N 5.25 g pot^{-1}, P_2O_5 2.75 g pot^{-1}, and K_2O 5.25 g pot^{-1}). The experimental treatments in the annual Chinese cabbage stage included (1) zero-N fertilizer, i.e., control (N 0 g pot^{-1}, P_2O_5 3.75 g pot^{-1}, and K_2O 6.25 g pot^{-1}); (2) NPK (N 6.25 g pot^{-1}, P_2O_5 3.75 g pot^{-1}, and K_2O 6.25 g pot^{-1}); and (3) BF (N 6.25 g pot^{-1}, P_2O_5 3.75 g pot^{-1}, and K_2O 6.25 g pot^{-1}). The specific maize and Chinese cabbage nutrient requirements were obtained from "Experimental Research and Statistical Analysis" [28].

According to the NPK fertilization strategy, N fertilizer was divided into basal fertilizer (60%) and topdressing fertilizer (40%). Urea was top-dressed in the NPK fertilization treatment during the maize jointing and cabbage rosette growth stages. P and K were applied as basal fertilizers in the zero-N fertilizer and NPK fertilization treatments. According to the BF treatment strategy, BF was used as a basal fertilizer in a one-time application. Mineral N, P, K, and BF refer to urea, superphosphate, potassium sulfate, and biochar-based slow-release fertilizer, respectively. BF is a slow-release biochar-based fertilizer (N 15%, P_2O_5 10%, and K_2O 15%), which is a new type of fertilizer made by mixing biochar and other chemical fertilizers through a particular process with a total nutrient content $\geq$ 40% and a carbon content (calculated as C) $\geq$ 6%, produced by Qinfeng Zhongcheng New Biomass Materials (Nanjing) Co., Ltd in Nanjing, China. Biochar was produced by pyrolyzing maize straw at a high temperature of 450 °C for 2 h under anaerobic conditions.

In Southwest China, the rotation of maize and vegetables is widely practiced, which was used in this experiment. The pot experiments used a maize (*Zea mays*)–Chinese cabbage (*Brassica campestris* L. spp. *pekinensis*) rotation system. The first season of maize was transplanted on April 19 and harvested on 10 September 2019; the second season of Chinese cabbage was transplanted on 20 October 2019 and harvested on 10 January 2020; the third season of maize was transplanted on 20 April, and harvested on 15 September 2020; the fourth season of Chinese cabbage was transplanted on 25 October 2020 and harvested on 15 January 2021. The experiment was performed under field conditions. As the maize and Chinese cabbage were transplanted, basal fertilizer was applied to the topsoil at a depth of 20 cm. The processes of transplanting and fertilizing are almost simultaneous. A standard chemical program was used to control weeds, insects, and diseases in the plots during the various crop growth stages of the maize and Chinese cabbage. No irrigation was applied during the growing season. The management of maize and Chinese cabbage in this pot experiment was the same as that in the fields.

2.3. Sampling and Measurements

Samples of fresh soil between 0 and 20 cm deep were collected at the seedling stage, jointing stage, heading stage, and harvest stage of maize and at the seedling stage, rosette stage, and harvest stage of cabbage. Surface debris was removed, and the samples were bagged, transported in a careful manner, and maintained at room temperature (25 °C). NH_4^+-N and NO_3^--N were measured using indigo blue colorimetry and ultraviolet spectrophotometry, respectively, according to Bao [29].

The starch, sugar, and crude protein contents of maize and the contents of amino acids, sugar, and vitamin C in the edible parts of cabbage were analyzed after the 2020 harvests.

The nutritional qualities of the maize grain and edible cabbage parts were determined according to Bao [29]. 3,5-Dinitrosalicylic acid was used to detect reducing sugars in maize grain and cabbage; the spectrophotometric method was used to determine the amino acids in cabbage; the Kjeldahl method was used to determine the crude protein content; anthrone colorimetry was used to determine the maize grain starch, and 2,6-dichloro-indophenol titration was used to determine the vitamin C content in cabbage. After being air-dried, weighed, and sieved through a 0.15 mm sieve, the total N of maize and cabbage samples was determined using the micro-Kjeldahl method [29].

2.4. Calculations

The plant height, stem diameter, and ear height of maize, and the leaf length, leaf width, and leaf number of Chinese cabbage were used as the representative maize and cabbage growth-related traits. The plant height and ear height of maize and the leaf length and leaf width of Chinese cabbage were measured using a ruler. The stem diameter of maize was measured using a Vernier caliper. Based on the methods reported by Hartmann et al. (2015) [30], the N fertilizer use efficiency (NUE) was calculated as follows: NUE = (UN − UN0)/FN × 100, where UN is the total N uptake of plants under fertilization (g plant^{-1}); UN0 is the total N uptake of plants without N fertilization (g plant^{-1}); FN is the amount of N fertilizer applied (g plant^{-1}). The sum of NH_4^+-N and NO_3^--N is inorganic N. Inorganic N includes NH_4^+-N and NO_3^--N.

2.5. Statistical Analyses

The significance of differences between soil and plant indicators was measured by one-way ANOVA. Duncan's multiple ranges (SSR) test was used to check the significance of treatment effects at $p < 0.05$. The statistical analysis was conducted using SPSS Version 16.0 (SPSS Inc., Chicago, IL, USA). The figures and tables were compiled using Excel 2016 and Origin 22.0.

3. Results

3.1. Crop Yields and Growth-Related Traits

As shown in Figure 1, the N treatments affected the crop yield in the maize–Chinese cabbage rotation (2019–2020). The yield of maize and Chinese cabbage in 2019–2020 under the BF treatment was the highest at 70.43 g plant^{-1}–103.55 g plant^{-1} and 484.00 g plant^{-1}–513.76 g plant^{-1}, respectively. Compared to zero-N, the yields of maize grain and Chinese cabbage significantly increased under the NPK and BF treatments. Compared with the NPK treatment, the BF treatment significantly improved the maize grain yield by 35.26% and 17.78% (Figure 1a,b) and the Chinese cabbage yield by 32.78% and 59.55%, respectively, in 2019 and 2020.

Figures 2 and 3 show the growth-related traits of maize and Chinese cabbage in 2019–2020 under different fertilization treatments. Compared to the zero-N treatment, the results of the variance analysis showed that the NPK treatment had significant effects on the ear height of maize in 2019 (Figure 2c), the leaf length and leaf number of Chinese cabbage in 2019–2020, and the leaf width of Chinese cabbage in 2020 (Figure 3a,b,d–f), and the BF treatment had significant effects on the plant height, ear height, and stem diameter of maize in 2019–2020 (Figure 2a–f) and the leaf length, leaf width, and leaf number of Chinese cabbage in 2019–2020 (Figure 3a–f). Figures 2 and 3 show that the growth-related traits of maize and Chinese cabbage in 2019–2020 under the BF treatment were significantly higher than those under the zero-N treatment. Compared to the NPK treatment, the BF treatment significantly improved the plant height, ear height, and stem diameter of maize by 7.65–8.77%, 4.20–9.35%, and 17.92–40.73%, respectively, in 2019–2020 (Figure 2a–f). The leaf width and leaf number of Chinese cabbage under the BF treatment increased by 15.96–19.84% and 9.09–20.00%, respectively, compared to the NPK treatment (Figure 3c–f).

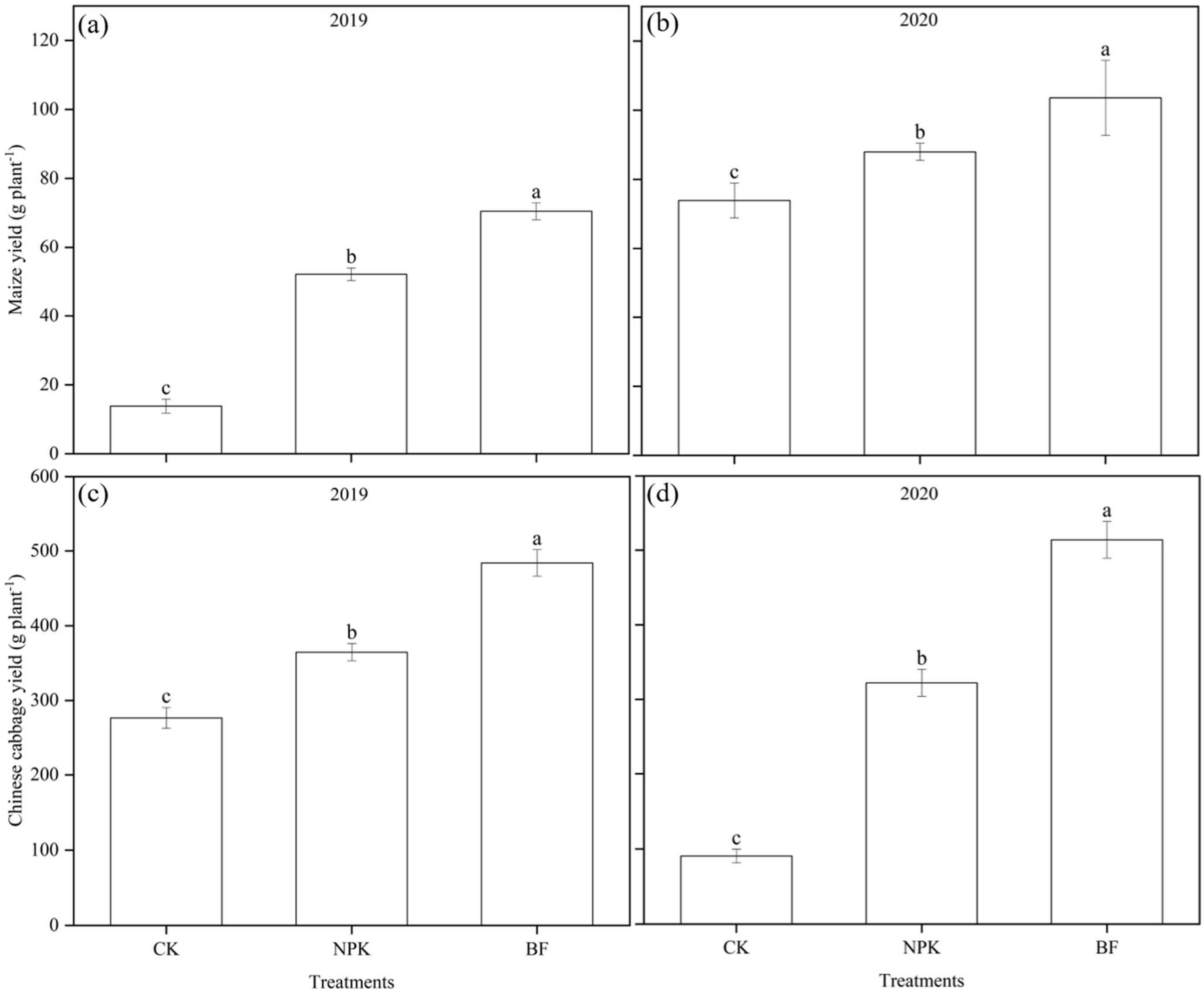

Figure 1. Yields of maize and cabbage in 2019–2020 under different N treatments. (**a**), Maize yield in 2019. (**b**), Maize yield in 2020. (**c**), Chinese cabbage yield in 2019. (**d**), Chinese cabbage yield in 2020. The error bars show the standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.2. *Crop N Uptake and Utilization Efficiency*

Figure 4 shows the N uptake of maize and Chinese cabbage in 2019–2020 under different fertilization treatments. Compared to the zero-N treatment, the N uptake of maize grain and Chinese cabbage increased with different types of fertilizer (Figure 3). Compared to the NPK treatment, the BF treatment significantly improved the N uptake of maize in 2019 (Figure 4a) but not of Chinese cabbage in 2020 (Figure 4d). There was no significant difference between the NPK and BF treatments in terms of the N uptake of maize in 2020 (Figure 4b) or the N uptake of Chinese cabbage in 2019 (Figure 4c).

Figure 5 shows the N utilization efficiency of maize and Chinese cabbage in 2019–2020 under the NPK and BF treatments. Compared with the NPK treatment, the BF treatment had the highest average N utilization efficiency in maize and Chinese cabbage, at 44.31 kg kg^{-1} and 40.73 kg kg^{-1}, respectively (Figure 5a–d).

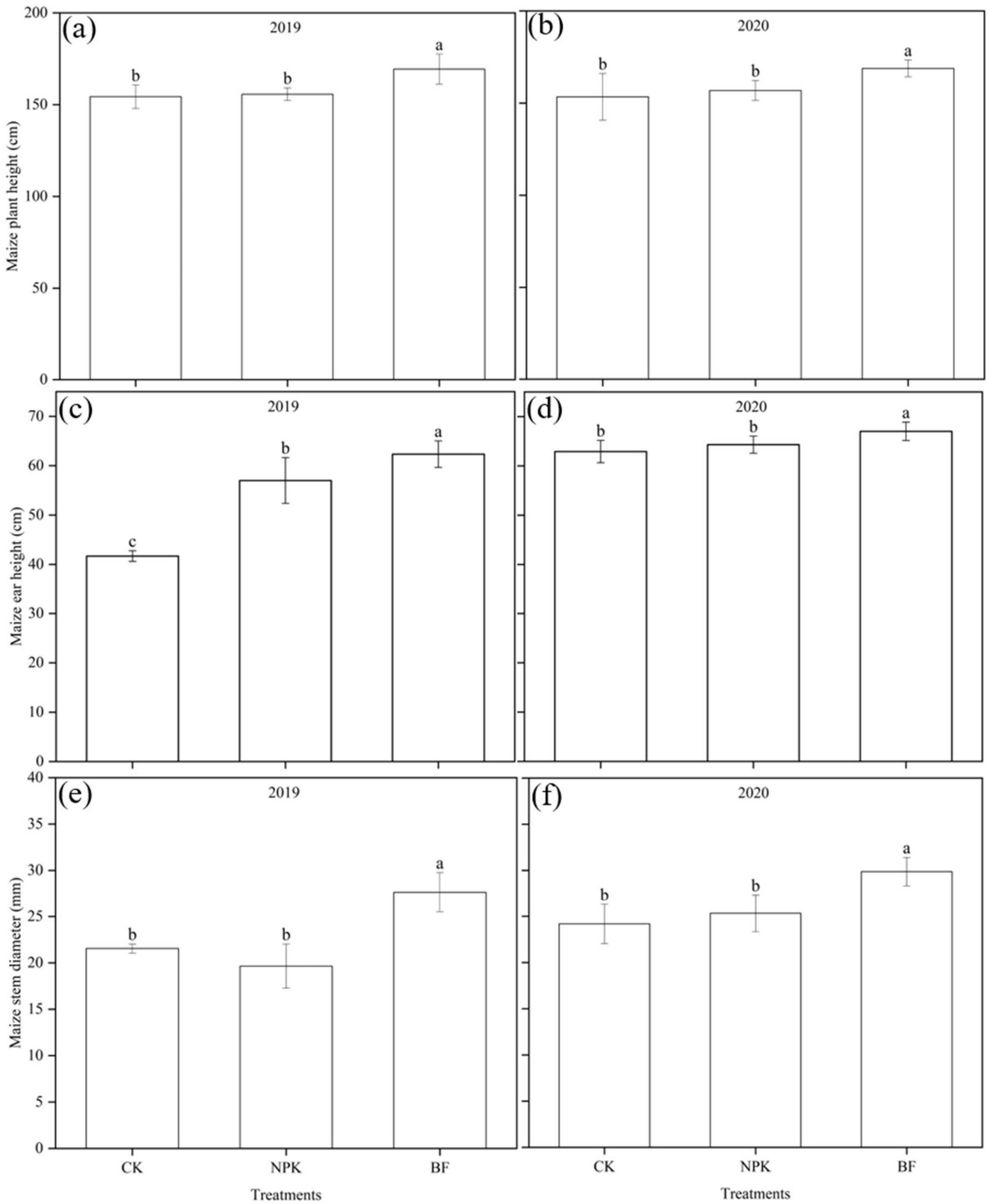

Figure 2. Growth-related traits of maize in 2019–2020 under different N treatments. (**a**), Plant height of maize in 2019. (**b**), Plant height of maize in 2020. (**c**), Ear height of maize in 2019. (**d**), Ear height of maize in 2020. (**e**), Stem diameter of maize in 2019. (**f**), Stem diameter of maize in 2020. The error bars show the standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments (p < 0.05).

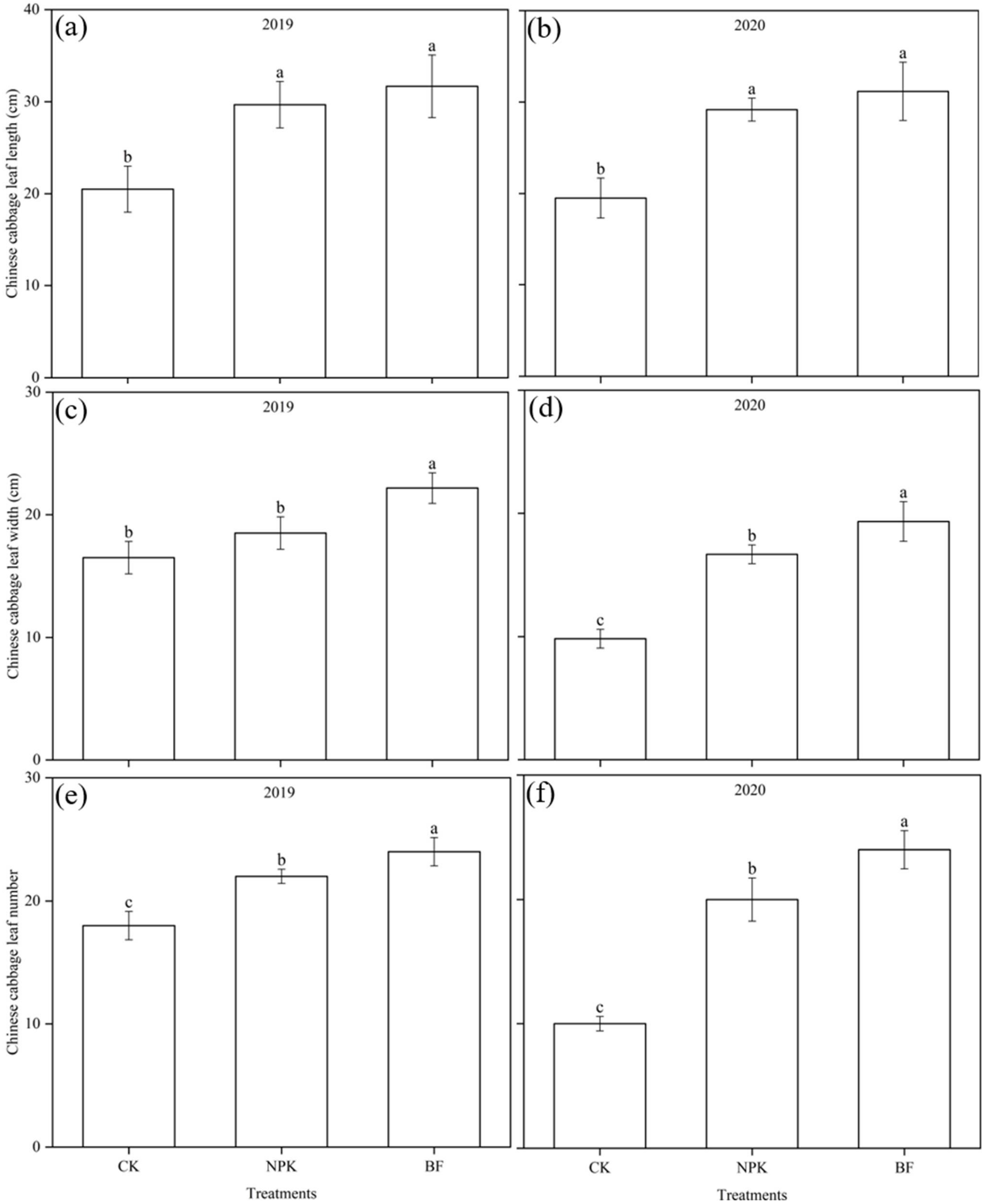

Figure 3. Growth-related traits of Chinese cabbage in 2019–2020 under different N treatments. (**a**), Leaf length of Chinese cabbage in 2019. (**b**), Leaf length of Chinese cabbage in 2020. (**c**), Leaf width of Chinese cabbage in 2019. (**d**), Leaf width of Chinese cabbage in 2020. (**e**), Leaf number of Chinese cabbage in 2019. (**f**), Leaf number of Chinese cabbage in 2020. The error bars show standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

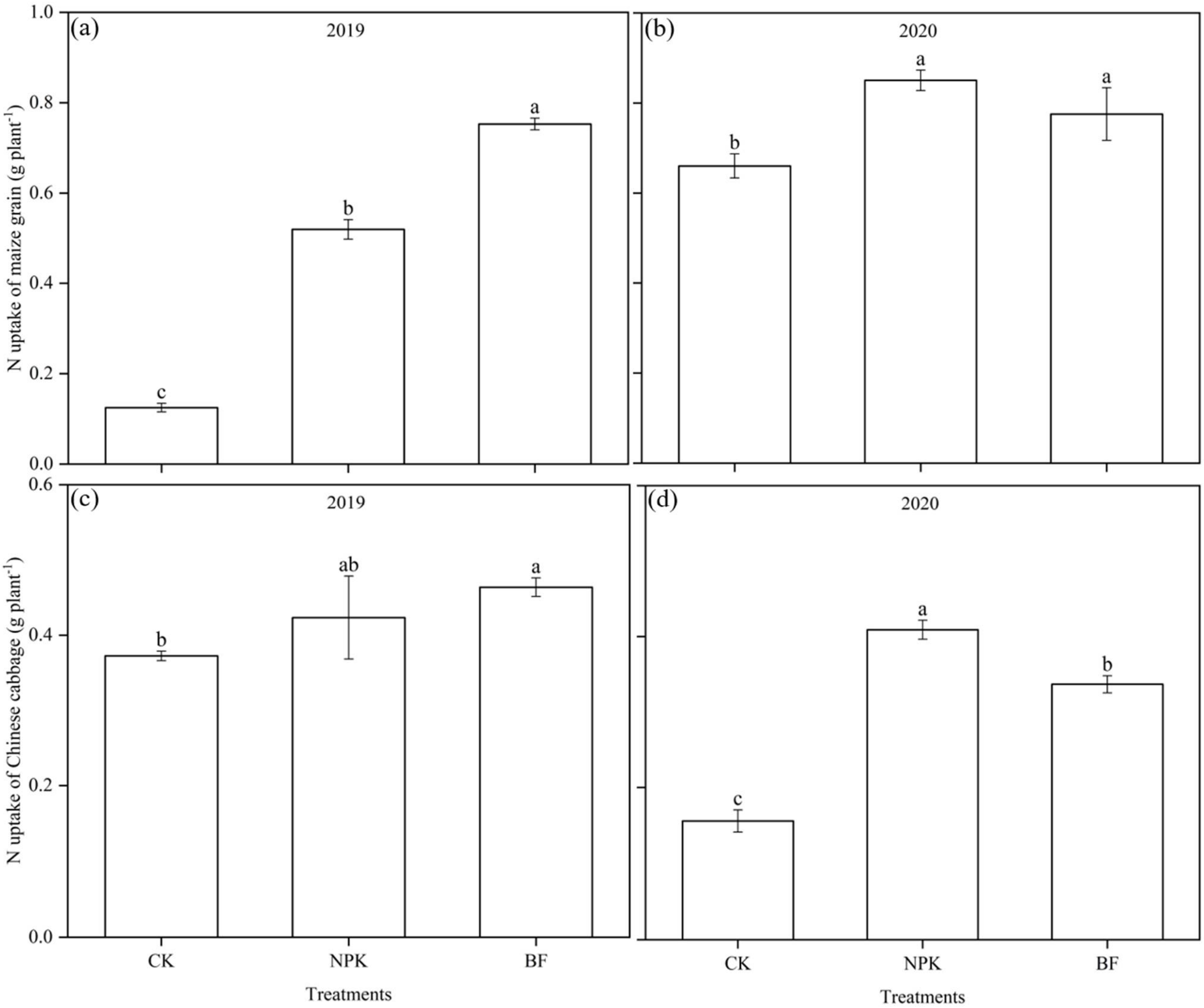

Figure 4. N uptake of maize and Chinese cabbage in 2019–2020 under different N treatments. (**a**), N uptake of maize in 2019. (**b**), N uptake of maize in 2020. (**c**), N uptake of Chinese cabbage in 2019. (**d**), N uptake of Chinese cabbage in 2020. The error bars show the standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments (p < 0.05).

3.3. Crop Quality

Figure 4 shows the nutritional quality of maize and cabbage under the different types of fertilizers. Compared with the zero-N treatment, the contents of maize grain sugar and crude protein under the NPK treatment significantly improved by 16.21% and 10.95%, respectively (Figure 6b,c), and the sugar content of Chinese cabbage under the NPK treatment significantly improved by 65.89% (Figure 6e). Compared to the zero-N treatment, the contents of maize grain starch, sugar, and crude protein under the BF treatment significantly improved by 6.56%, 15.36%, and 12.58%, respectively (Figure 6a–c). The contents of Chinese cabbage amino acids, sugar, and vitamin C under the BF treatment improved significantly in comparison to the zero-N treatment by 17.98%, 91.23%, and 15.43%, respectively (Figure 6d–f). In comparison with the NPK treatment, the content of maize grain starch under the BF treatment significantly improved by 4.91% (Figure 6a), and the contents of Chinese cabbage amino acids, sugar, and vitamin C under the BF treatment significantly increased by 13.84%, 15.28%, and 19.94%, respectively (Figure 6d–f).

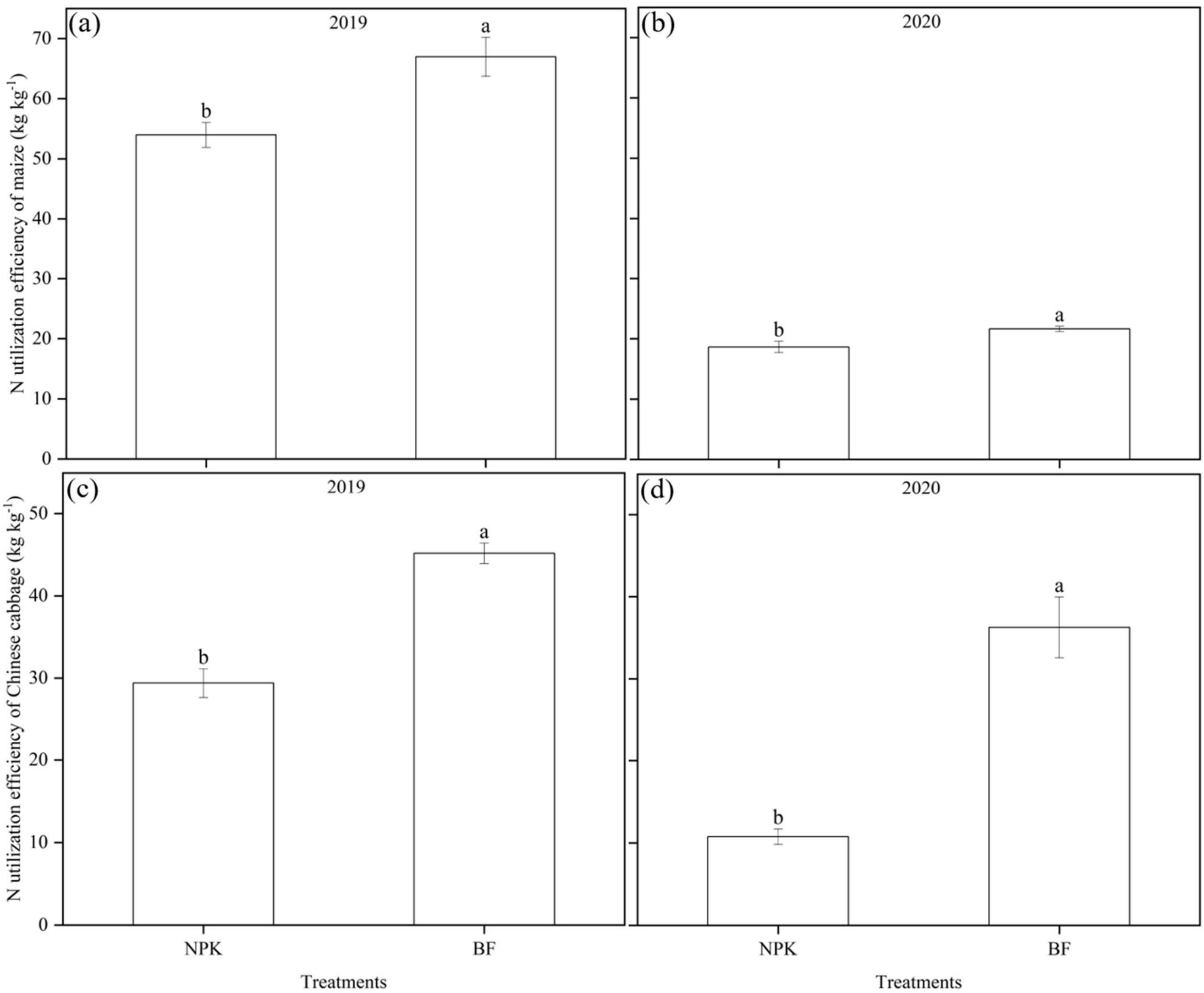

Figure 5. N utilization efficiency of maize and Chinese cabbage in 2019–2020 under different N treatments. (**a**), N utilization efficiency of maize in 2019. (**b**), N utilization efficiency of maize in 2020. (**c**), N utilization efficiency of Chinese cabbage in 2019. (**d**), N utilization efficiency of Chinese cabbage in 2020. The error bars show the standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

3.4. Dynamic Changes in Soil NH_4^+-N, NO_3^--N, and Inorganic N

Figure 7a shows the dynamic changes in soil NH_4^+-N under different fertilization treatments of maize and cabbage at different growth stages. With the development of the maize and cabbage growth stages, soil NH_4^+-N showed a mild fluctuation and a declining trend under zero-N fertilizer. The 2020 cabbage harvest stage had the lowest content of soil NH_4^+-N (Figure 7a). The content of soil NH_4^+-N under the NPK and BF treatments was higher than that under the zero-N treatment in each growth stage of maize and cabbage. In both BF and NPK treatment soils, the trend of NH_4^+-N increased during the rotation cycle of maize and cabbage and then decreased. At all growth stages of the continuous maize and cabbage rotation, the content of soil NH_4^+-N under the BF treatment was higher than that under the NPK treatment.

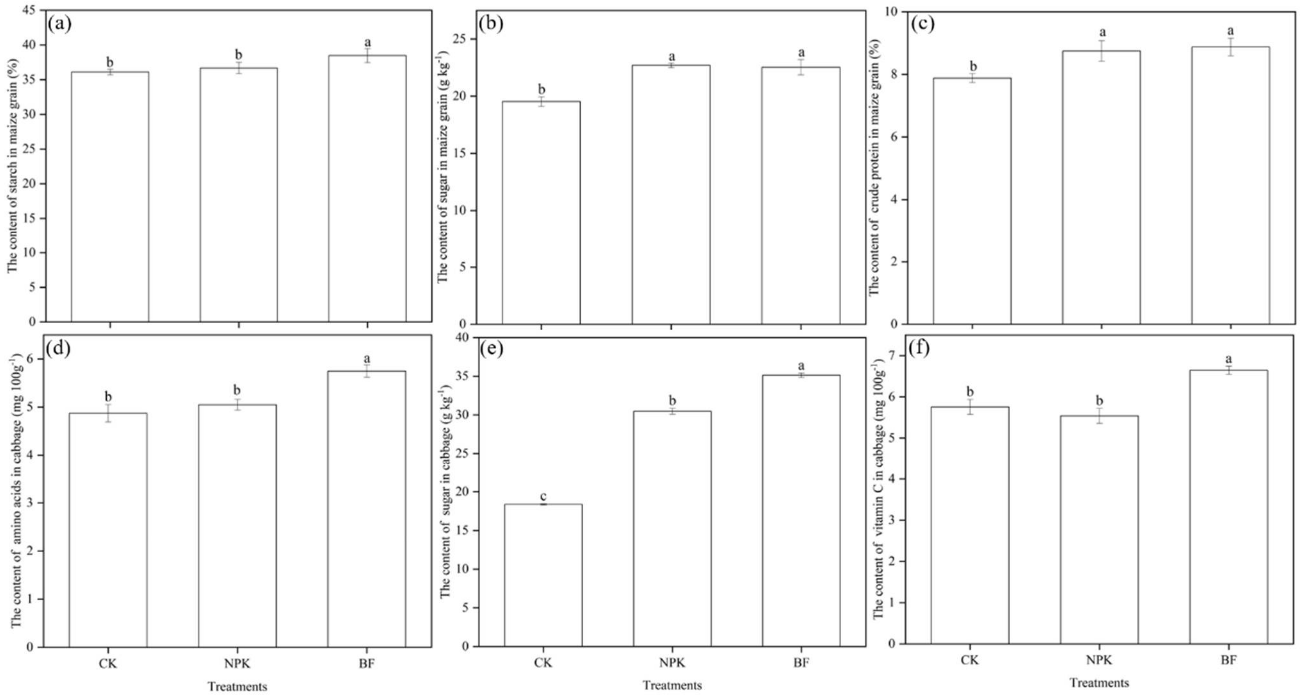

Figure 6. Quality of the maize and cabbage under different N treatments in 2020. (**a**), The content of starch in maize grain. (**b**), The sugar content in maize grain. (**c**), The content of crude protein in maize grain. (**d**), The amino acid content in cabbage. (**e**), The sugar content in cabbage. (**f**), The content of vitamin C in cabbage. The error bars show the standard deviations of the means (n = 3). Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

Figure 7b shows dynamic changes in soil NO_3^--N under different fertilization treatments of maize and cabbage at different growth stages. With the development of the maize and cabbage growth stages, the soil NO_3^--N showed a mild fluctuation and an increasing trend in the zero-N fertilizer treatment, whereas the opposite was true for the NH_4^+-N change trend. Compared to the zero-N treatment, the soil NO_3^--N under the NPK fertilizer treatment was significantly increased only at the 2019 maize jointing and heading stages, the 2019 cabbage harvesting stage, the 2020 maize heading and harvesting stages, and the 2020 cabbage seedling and rosette stages. At all growth stages of the continuous maize and cabbage rotation, the soil NO_3^--N under the BF treatment was higher than that under the zero N treatment. The soil NO_3^--N under the BF treatment (except for the 2019 maize jointing stage) was higher than that under the NPK treatment in each stage of the maize and cabbage rotation.

Figure 7c shows dynamic changes in soil inorganic N under different fertilization treatments of maize and cabbage at different growth stages. Soil inorganic N under the zero-N treatment at all stages was low and tended to fluctuate slightly. At all growth stages of the continuous maize and cabbage rotation, the soil inorganic N under the NPK and BF treatments was higher than that under the zero N treatment. The soil inorganic N under the BF treatment (except for the 2019 maize jointing and 2020 cabbage rosette stages) was higher than that under the NPK treatment at each stage of the maize and cabbage rotation.

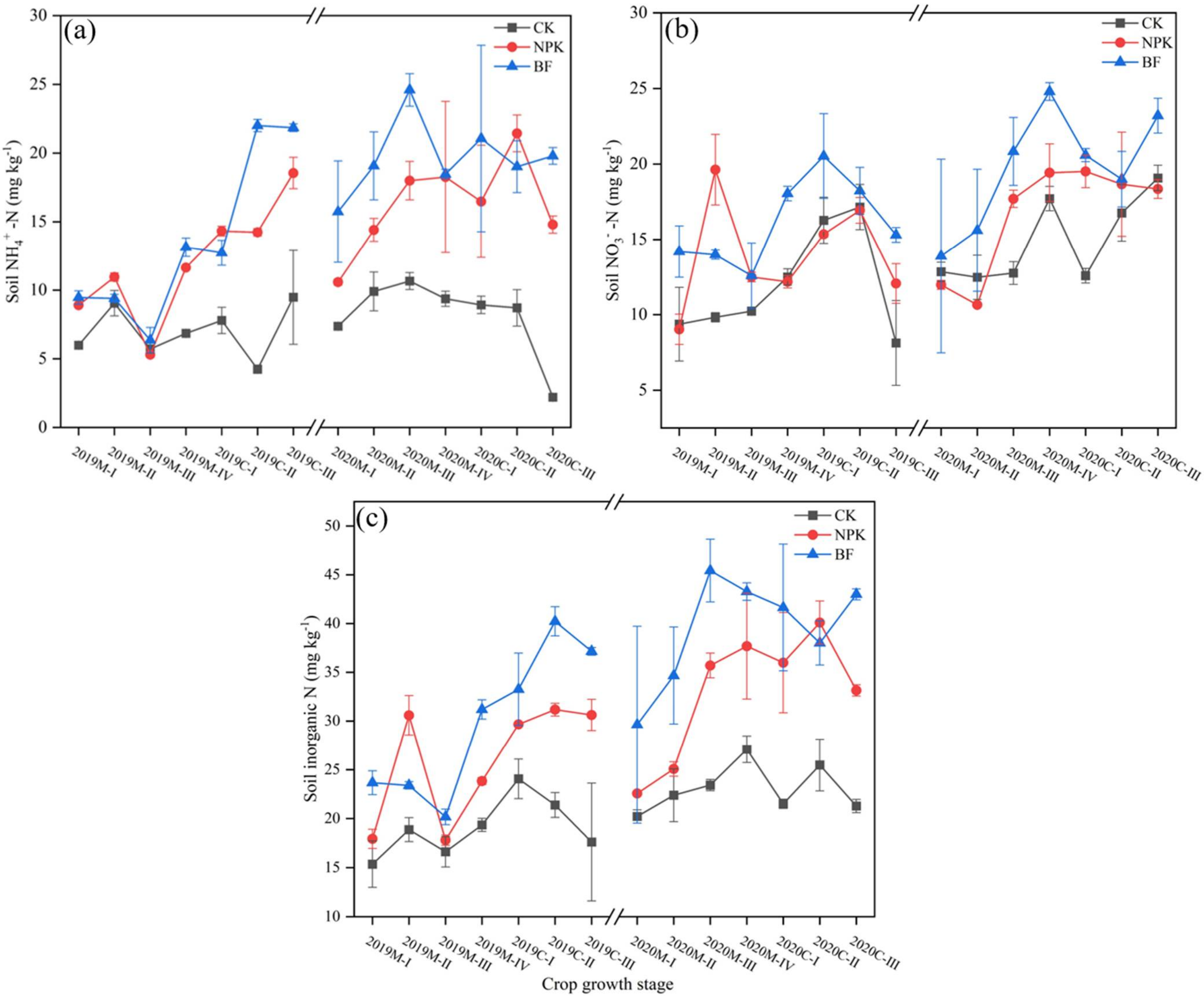

Figure 7. Dynamic changes in the soil NH_4^+-N, NO_3^--N, and inorganic N levels under different fertilization treatments of maize and cabbage at different growth stages between 2019 and 2020. (**a**), The dynamic changes in soil NH_4^+-N (**b**), the dynamic changes in soil NO_3^--N (**c**), The dynamic changes in soil inorganic N. 2019M-I, 2019M-II, 2019M-III, and 2019M-IV represent the seedling stage, jointing stage, heading stage, and harvest stage of maize, respectively, in 2019. 2019C-I, 2019C-II, and 2019C-III represent the seedling stage, rosette stage, and harvest stage of cabbage, respectively, in 2019. 2020M-I, 2020M-II, 2020M-III, and 2020M-IV represent the seedling stage, jointing stage, heading stage, and harvest stage of maize, respectively, in 2020. 2020C-I, 2020C-II, and 2020C-III represent the seedling stage, rosette stage, and harvest stage of cabbage, respectively, in 2020. The error bars show the standard deviations of the means (n = 3).

4. Discussion

To maximize crop yield, fertilization is a critical agricultural practice, and crop yield is strongly influenced by the type and number of fertilizers used [31,32]. Changes in the maize grain and cabbage yield under the different N fertilization treatments (Figure 1) showed a significant but strong effect of N fertilizer on maize grain and cabbage production, which were higher under the NPK and BF treatments than under zero N. Crop yield is affected by the number of fertilizers as well as the type [33]. On the whole, reasonable N fertilizer use appropriately increases crop yields [12,34]. The application of BF enhanced crop productivity compared to conventional fertilization and no fertilizer application, according to Melanie et al. 2022 [22]. The results of this study show that in comparison with the NPK treatment, the BF application rates improved the yields of maize grain and Chinese cabbage over the two rotation cycles (2019–2020). Similar results have also been found in other studies examining the effects of carbon-based fertilizers on crop yields [3,15]. BF maintains the high availability of soil nutrients during crop growth while improving crop nutrient utilization efficiency, thus promoting crop yield.

The most critical agronomic traits of maize are plant height, ear height, and stem diameter, all of which are directly related to crop lodging resistance, biomass production, and yield [35–38]. In general, different effects were observed for each of the agronomic traits of maize (plant height, ear height, and stem diameter) when N fertilization was applied, as shown in Figure 2. In comparison with the zero-N treatment, the NPK fertilizer application only improved maize ear height, which resulted in poor maize lodging resistance. In contrast, BF increased plant height, ear height, and stem diameter of maize simultaneously and increased maize lodging resistance more effectively. Compared with the zero-N treatment, the NPK and BF applications significantly increased the Chinese cabbage leaf length, leaf width, and leaf number (Figure 3). Chinese cabbage leaf length, leaf width, and leaf number improved more with BF application than with NPK fertilization (Figure 3). Hence, biochar-based slow-release fertilizer is more effective in improving Chinese cabbage biomass production. Biochar has improved the growth characteristics of different crops [39].

In agricultural production, efficient N management is crucial to minimize N losses and improve N uptake and N use efficiency [40,41]. It is important to note that inefficient fertilizers can lose large amounts of nutrients through leaching, volatilization, denitrification, immobilization, erosion, and runoff, reduce crop nutrient efficiency, and cause environmental pollution. Crops with high N uptake efficiency have high yields, and crop yield is correlated with N uptake [42,43]. Agricultural development requires slow-release fertilizer, especially when nutrient losses are high. Slow-release fertilizer has the advantage of improving the nutrient absorption efficiency of crops, resulting in more uniform fertilizer release during the growing season through one-time fertilization and less excessive absorption of nutrients by crops [44]. Compared to the zero-N treatment, the NPK and BF applications improved the N uptake of the maize grain and Chinese cabbage (Figure 4). Compared to NPK application, the BF treatment significantly increased the N utilization efficiency of maize and Chinese cabbage (Figure 5). Thus, BF was able to meet the N nutrient demands of maize and cabbage better than NPK. This occurred because carbon-based slow-release fertilizer contains biochar that adsorbs N through chemical and physical adsorption. The efficiency of different N sources depends on the type of N fertilizer used [45]. Carbon-based fertilizer, as a combined product of nutrients and biochar, can enhance the positive interactions between N fertilizer and biochar in soils [46]. N from pure urea is an amide N, and all N in BF is an efficient N form [4]. Biochar is considered a key property for retaining soil nutrients in a form that is suitable for crop use [47]. The pore structure is one of the main reasons for the improvement of the slow-release performance of biochar-based slow-release fertilizers [48]. A study revealed that by using an infiltration method of urea and biochar, urea penetrated adequately into the pores of the biochar and was evenly distributed on its surface; this method met the N requirements of crops better than the direct mixing of biochar and urea [4]. Biochar's high organic carbon content, large surface area, high microporosity, and range of functional groups also help plants retain nutrients [16].

Crop quality is important for human health and economic value and optimizing the management of N fertilizer can significantly enhance crop quality [49,50]. Maize grain consists mainly of starch (70%) and protein (10%), while the quality of grains is largely determined by the amount and composition of the protein [51]. The NPK treatment significantly increased the maize grain sugar and crude protein contents compared to the zero-N treatment (Figure 6b,c). However, the BF treatment not only significantly increased the maize grain sugar and crude protein contents but also significantly increased the maize grain starch content (Figure 6a–c). There was a significant increase in maize grain starch in the BF treatment compared to the NPK treatment (Figure 6a). Studies have demonstrated that the appropriate application of N fertilizer can maximize the nutritional value of maize [52,53]. Moreover, the quality of the nutritional components of vegetables is very important for human health [54]. Compared to the zero-N treatment, the NPK treatment significantly increased the cabbage sugar content (Figure 6e). The BF treatment significantly improved not only the cabbage sugar but also the amino acid and vitamin C contents (Figure 6d–f). Additionally, there were significant improvements in the contents of amino acids, sugar, and vitamin C in cabbage under the BF treatment compared to the NPK treatment (Figure 6d–f).

The different N treatments had varying effects on the dynamics and mechanisms of soil inorganic N and N forms in the maize and cabbage rotation system (Figure 7). Compared with the zero-N treatment, the addition of N fertilizer enhanced NH_4^+-N, NO_3^--N, and inorganic N in the soil during each growth stage of maize and cabbage, improving the utilization of crop N as well as the yield and quality. The N forms under the zero-N treatment showed small fluctuations. In stark contrast, the N forms in the NPK and BF treatments fluctuated upward with a wide fluctuation range. We found an interesting phenomenon in which, as the maize and cabbage rotation continued, conventional N fertilizer mainly had a strong and positive impact on soil NH_4^+-N (Figure 7a), whereas the effect on NO_3^--N was relatively weak (Figure 7b). In contrast, NH_4^+-N and NO_3^--N continued to increase in the soil treated with BF. Biochar-based slow-release fertilizers occur in the plant-absorbable form of N, so they have different effects on soil N forms. Studies have found that biochar use significantly increases plant uptake of added NO_3^--N while reducing the uptake of added NH_4^+-N [55]. An optimal N rate regime balances crop demand with soil availability [56]. Soil NO_3^--N accumulation is significantly related to crop yield and aboveground biomass [57]. Therefore, biochar-based slow-release fertilizer has a higher crop N use efficiency and higher yield potential than conventional N fertilizer.

In general, the N release rate of the common fertilizer at the earlier stage of maize and cabbage growth was higher. Nevertheless, it was relatively lower at the later stage of crop growth. In contrast, the N nutrient release rate of the biochar-based slow-release fertilizer at the earlier stage of crop growth was lower, but it was relatively higher at the later stage of development. These nutrient release dynamics are more in line with the nutrient demand regulation of crop growth, and inorganic N was high, as shown in Figure 7c. Therefore, the application of BF can significantly improve the efficient uptake and utilization of nutrients by crops, thus increasing crop yield levels and improving quality. Most plants grow best with a mixture of NH_4^+-N and NO_3^--N, while NH_4^+-N as a sole N source may inhibit their growth [41,58]. Urea, a conventional N fertilizer, is rapidly released into the soil upon application. The N in urea is easily hydrolyzed to ammonium N, the majority of which is then converted to nitrate by rapid nitrification, which can negatively affect the soil environment, groundwater, and atmosphere through leaching, runoff, and volatilization [45,59–61]. Figure 7c shows that in 2019, traditional N fertilizer sharply increased the soil inorganic N levels after the jointing stage of maize and then sharply decreased. In contrast, in the 2019–2020 growing season, the soil inorganic N level continued to increase gradually under the BF treatment, which also indicated the slow release and long duration of N nutrients from the slow-release fertilizer. Biochar can reduce the leaching of dinitrate and ammonium in the soil, thus significantly increasing the soil N content [62]. Biochar-based fertilizer is an effective slow-release fertilizer that reduces soil inorganic N loss in a maize and cabbage rotation system.

5. Conclusions

The biochar-based slow-release fertilizer significantly improved the crop yield, growth-related traits, quality, and N utilization efficiency in this maize–Chinese cabbage rotation system. Biochar-based slow-release application increased soil NH_4^+-N, NO_3^--N, and inorganic N. The biochar-based slow-release nutrient pattern more closely matched crop nutrient needs as each stage of plant growth advanced. The application of biochar-based slow-release fertilizer is a nutrient-efficient management strategy for maize–Chinese cabbage rotation systems, increasing crop productivity while reducing negative environmental impacts and promoting sustainable agriculture. We expect that the selection of efficient slow-release fertilizers in maize and vegetable rotations will sustainably increase N efficiency and crop production potential in the hilly area of Southwest China.

Author Contributions: Conceptualization, H.Z., T.X. and H.X.; methodology, H.Z.; software, H.Z.; validation, H.Z., H.X. and T.X.; formal analysis, H.Z.; investigation, H.Z. and T.X.; writing—original draft preparation, H.Z.; writing—review and editing, H.Z. and M.G.; visualization, H.Z.; supervision, M.G. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financially supported by the National Key Research and Development Plan of China (Grant No. 2018YFD0200705).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data will be provided upon request by the corresponding author.

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

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