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Biochar Can Partially Substitute Fertilizer for Rice Production in Acid Paddy Field in Southern China

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Abstract: Biochar application has been confirmed as an efficient way to increase the productivity of the agricultural system. However, the potential of biochar combined with reducing fertilization on the yield, and the fertilizer utilization efficiency of the rice (*Oryza sativa*) farming system on acidic soil remains to be further studied. Field micro-plot experiments with two factors were performed in 2018 and 2019 to evaluate the responses of the rice yield and nutrient utilization to the combined application of biochar (60, 80, and 100 t/ha) and fertilizer reduction (70%, 85%, and standard doses of N-P-K fertilizer). Taoyouxiangzhan and Taiyou 553 were used in the late growing season of 2018 and 2019, respectively. The results showed that compared with the control without adding biochar under standard fertilization, 70% doses of fertilizer application had no negative effects on the yield and the N, P, and K accumulation of rice after biochar application. K accumulation of rice increased with the increase of biochar application. The partial productivity of N, P, and K fertilizers increased as the fertilizer was decreased. The agronomic efficiency of N, P, and K fertilizers significantly increased after the combined applications of biochar and fertilizer. In both years, micro-plots with 70% doses of fertilizer had the highest N and P physiological efficiency, as well as K physiological efficiency in 2019. Compared with the control under standard fertilization, utilization efficiency of N, P, and K fertilizer under different biochar and fertilizer combinations significantly increased by 34.24~75.48%, 27.44~84.84%, and 78.52~166.70%, respectively. To sum up, biochar can partially substitute fertilizer for rice production in acid paddy fields in southern China. When the amount of biochar added is ≥60 t/ha, 70% doses of fertilizer application can still ensure the nutrient absorption of rice, improve the fertilizer utilization efficiency, and ensure the stable yield of rice.

Keywords: biochar; fertilizer reduction; yield; nutrient utilization; acid paddy field

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1. Introduction

Rice is one of the main grain crops, and its production status directly affects the national food security in China. The perennial planting area of rice is about 30 million hectares, and the rice yield accounts for more than 30% of the total grain yield in China [1]. Fertilization is an important way to achieve a high and stable yield of rice. China is the country with the largest amount of fertilizer application in the world. The average rate of nitrogen, phosphorus, and potassium fertilizer used in a single season of paddy field is 173 kg/ha, 68 kg/ha, and 99 kg/ha, respectively [1], but the use efficiency of nitrogen, phosphorus, and potassium fertilizer is 27–35%, 11–13%, and 29–33%, respectively [2]. Excessive fertilizer input not only leads to the decline of fertilizer utilization efficiency [3], but also causes a series of ecological and environmental problems such as soil quality degradation [4], agricultural non-point source pollution aggravation [5,6], and greenhouse gas emission increase [7]. Reasonable reductions of fertilizer input and optimization of fertilizer application is of great significance for ensuring a high and stable rice yield and maintaining the sustainable development of the rice field ecosystem.

Biochar is the solid product of the thermal degradation of organic matter under oxygen-limited conditions [8]. The combined application of biochar and fertilizer has almost positive effects on crop growth and yield [9,10]. The complementary or synergetic effects of biochar and fertilizer can eliminate the problem in that biochar usually lacks nutrients and competes with crops for effective nutrients in soil [11], and the addition of biochar can help to prolong the release period of available nutrients in fertilizers and reduce nutrient loss [12,13]. Meta-analysis results showed that biochar application increased rice yield and nitrogen use efficiency by 10.73% and 12.04%, respectively [9]. Compared with fertilization alone, combined applications of biochar and fertilizer increased grain yield by 10–16%, as well as nitrogen and phosphorus use efficiency by 20–53%, and 38–230%, respectively [14]. Research on the rational application of biochar and fertilizer is beneficial to improve the fertilizer use efficiency by crops and reduce the nutrient loss of farmland.

The red soil hilly region of southern China is a region that has the highest cultivation index, but its soil and water loss is most severe due to the sticky and heavy soil texture, poor water permeability, and erratic seasonal rainfall. In addition, unreasonable tillage and excessive fertilization lead to soil acidification and fertility decline, aggravating soil erosion, which subsequently restricts the sustainable development of local agriculture [15]. Biochar is therefore a potential soil conditioner to improve the situation. Our previous five year field experiment showed that compared with the standard fertilization without biochar application, combined applications of biochar and fertilizer significantly promote rice growing development and increase grain yield in the acidic paddy of this region [10]. The study area of this experiment was located in Hunan Province, which has the largest rice planting area and the second largest yield in China [16], and the average use efficiency of nitrogen, phosphorus, and potassium fertilizer by rice is 36.6%, 16.6% and 41.0%, respectively [17]. Three questions were attempted to answer in this study, which were as follows: (1) how do rice yield and fertilizer use efficiency respond to different amounts of biochar addition and fertilizer reduction? (2) Is it possible to reduce fertilizer amount without reducing production after applying biochar in acid paddy field in southern China? (3) If possible, how much can be reduced?

2. Materials and Methods

2.1. Study Area

A field micro-plot experiment was conducted at the Yunyuan Experimental Farm of Hunan Agricultural University, Changsha, Hunan Province of China in 2018–2019. The soil used in the experiment was taken from the upper 20 cm layer of a rice field at the Changan Experimental Farm of Hunan Agricultural University, Changsha, Hunan Province of China. Changsha has a subtropical humid monsoon, with a mean annual precipitation of 1380–1533 mm, and a mean annual temperature of 18.28–18.52 °C. The soil was paddy soil derived from red earth with 5.14 pH, 13.8 g/kg organic carbon, 1.6 g/kg total nitrogen, 0.8 g/kg total phosphorus, 12.5 g/kg total potassium, 159.8 mg/kg alkali hydrolyzable nitrogen, 50.1 mg/kg, and 132.6 mg/kg available phosphorus and potassium, respectively.

2.2. Experimental Design

Using two specific factors (namely biochar addition and fertilizer reduction), a completely random design, field micro-plot experiment was set up with two controls (CK: standard doses of N-P-K without biochar application; and F0: no fertilization and no biochar application) and nine treatment combinations, including three biochar (B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; and B3: biochar application of 100 t/ha) and three fertilizer application rate (F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K). In total, there were 11 treatments (B1F1, B2F1, B3F1, B1F2, B2F2, B3F2, B1F3, B2F3, B3F3, CK, and F0), and each treatment had 3 micro-plots as replicates. The standard dose of N-P-K corresponds to 150 kg N/ha, 75 kg P_2O_5/ha, and 100 kg K_2O/ha, respectively.

The micro-plot was constructed with a rectangular plastic basin (34 cm height, 121 cm length, and 89 cm width). The soil was mixed first and then used to fill the plastic basin with a depth of ~25 cm. The commercially available biochar (pH 8.32, 56.8 g/kg total C, 0.4 g/kg total N, 1.67 g/kg total P, 2.13 g/kg total K, 25.3 mg/kg alkali hydrolyzed N, 23.4 mg/kg Olsen-P, 153 mg/kg available K, and a 6.58 cmol/kg cation exchange capacity) was produced from rice husks by pyrolysis at 500 °C for 5 h. Biochar was applied only once with the basal fertilizer before rice transplanting in the first season and no further additions in the second season.

Rice plants of both years were grown during the late growing season from July to October. Taoyouxiangzhan (hybrid, released in 2015) and Taiyou 553 (hybrid, released in 2019) were used in the experiment at two growing seasons (2018 and 2019), respectively. Each year, pre-germinated seeds were sown in a seedbed on 20 June to raise seedlings. Twenty-day-old seedlings were transplanted at a hill spacing of 16.7 cm × 20 cm with two seedlings per hill. For both growing seasons, nitrogen fertilizer was applied in three splits: 50% as basal fertilizer before transplanting, 20% as tillering fertilizer at 1 week after transplanting, and 30% as panicle fertilizer at panicle initiation. Phosphate fertilizer was all applied as a basal fertilizer before transplanting. Potassium fertilizer was applied in two splits: 80% as basal fertilizer before transplanting, and 20% as panicle fertilizer at panicle initiation. Insects, diseases, and weeds were intensively controlled by chemicals and manual work to avoid yield loss.

2.3. Sampling and Measurements

Grain yield was determined from 25 hills in each micro-plot. Grains were hand-threshed, filled, and unfilled grains (including half-filled and empty grains) were separated by submerging them in tap water. Filled grains were dried in an oven first at 105 °C for 0.5 h, and then at 80 °C to a constant weight. Grain yield was calculated and then was adjusted to the standard moisture content of 13.5%. Five representative hills with the average tiller number from each micro-plot were sampled at the maturity stage and separated into stems, leaves, and spikes to determine the biomass and N, P, and K uptake by each organ. The oven-dried samples were ground to a powder and approximately 0.5 g of each powder was digested with a mixture of H_2SO_4-H_2O_2 to determine P and K content with inductively coupled plasma-optical emission spectrometry (ICP-OES). N content was determined by combustion in a Vario EL III Elemental Analyzer (Elementar Analysen Syetem GmbH, Germany).

2.4. Calculations

Based on the methods reported by Zhang et al. (2008) [3], the fertilizer use efficiency was calculated as follows:

$$\text{Partial productivity (kg/kg)} = Y/F \tag{1}$$

$$\text{Agronomic efficiency (kg/kg)} = (Y - Y_0)/F \tag{2}$$

$$\text{Physiological efficiency (kg/kg)} = (Y - Y_0)/(U - U_0) \tag{3}$$

$$\text{Fertilizer use efficiency} = (U - U_0)/F \times 100\% \tag{4}$$

Y—Crop yield in the fertilization plot (kg/ha)
Y_0—Crop yield in the unfertilized plot (kg/ha)
U—Fertilizer uptake of plants in the fertilization plot (kg/ha)
U_0—Fertilizer uptake of plants in the unfertilized plot (kg/ha)
F—the amount of fertilizer applied (kg/ha)

2.5. Statistical Analysis

The results are presented as mean ± standard deviation. The significance of differences between each BF combinations and the controls was measured by the one-way ANOVA and

LSD multiple comparison analysis. The significance of the main effects and the interactions of biochar application and fertilizer reduction was measured by the two-way ANOVA without the controls, and the Duncan's multiple ranges (SSR) test was used to check the significance at $p < 0.05$. The statistical analysis was conducted using SPSS Version 16.0 (SPSS Inc., Chicago, IL, USA). The figures were compiled using Excel 2019 and SigmaPlot 11.0.

3. Results

3.1. Yield and Nutrient Accumulation

Grain yield in 2018~2019 under different biochar and fertilizer treatment combinations was 8.06~9.51 t/ha and 7.52~8.66 t/ha, respectively, which significantly increased by 22.3~44.3% and 13.9~31.1%, respectively, when compared with the control F0 (with values of 6.59 t/ha in 2018 and 6.61 t/ha in 2019, respectively) (Figure 1). There were no significant differences between these treatment combinations and the control CK in 2018 (8.19 t/ha). Compared with the control CK (7.35 t/ha), grain yields under the treatments of B2F1, B3F1, B1F3, B2F3, and B3F3 significantly increased by 13.7%, 17.7%, 17.8%, 16.3% and 14.9% in 2019, respectively. There were no significant differences found among these combinations in both years.

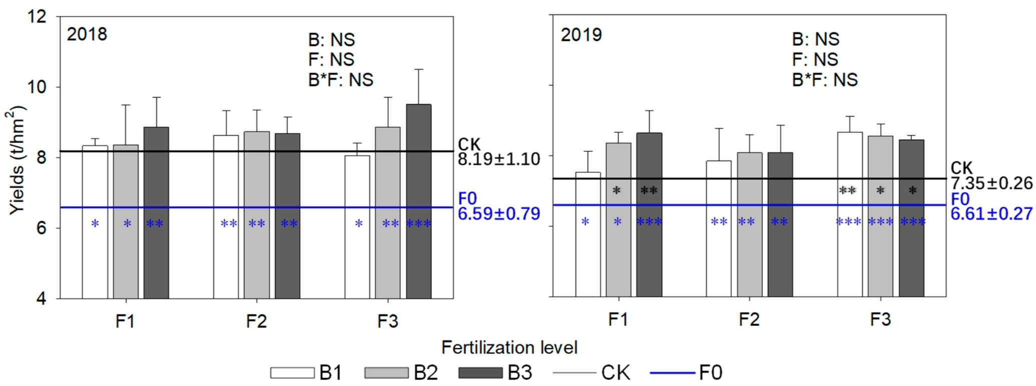

Figure 1. Grain yield of Taoyouxiangzhan (2018) and Taiyou 553 (2019) under different treatments. CK: standard doses of N-P-K without biochar application; F0: no fertilization and no biochar application; B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; B3: biochar application of 100 t/ha; F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K. Mean and standard deviation of the two controls are listed beside the corresponding lines. "*", "**" and "***" indicate the significant difference between the BF combinations and the control CK/F0 at the 5%, 1% and 0.1%levels, respectively.

Accumulation of N, P, and K of rice aboveground at harvest time in 2018~2019 under the different biochar and fertilizer treatment combinations was significantly higher than those in the control F0 ($p < 0.001$, Figure 2). Compared with the control CK, a reduced fertilizer application did not lead to the reduction of N, P, and K accumulation when combined applications with biochar (Figure 2). F1 combinations had the lowest N, P, and K accumulation than the combinations of F2 and F3. K accumulation in rice aboveground increased with the increase of biochar application (Figure 2).

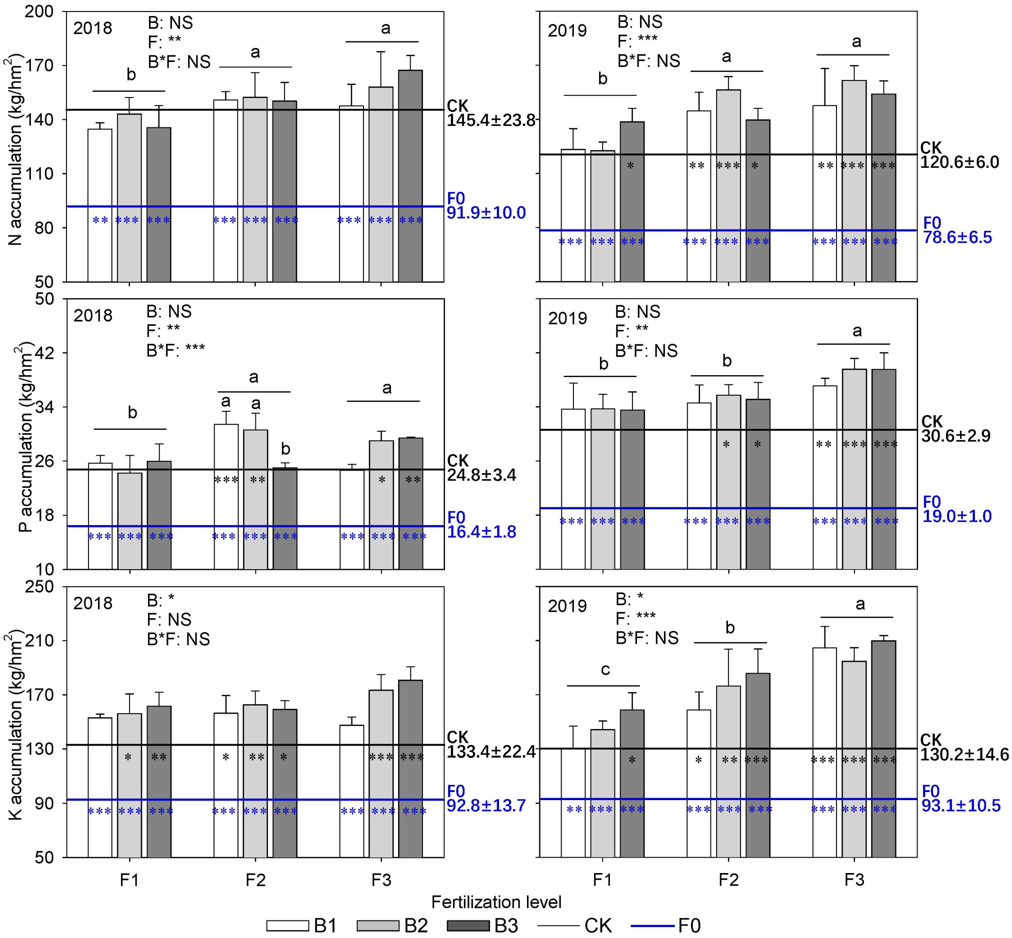

Figure 2. Nutrient accumulation of Taoyouxiangzhan (2018) and Taiyou 553 (2019) under different treatments. CK: standard doses of N-P-K without biochar application; F0: no fertilization and no biochar application; B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; B3: biochar application of 100 t/ha; F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K. Mean and standard deviation of the two controls are listed beside the corresponding lines. "*", "**" and "***" indicate the significant difference between the BF combinations and the control CK/F0 at the 5%, 1%, and 0.1% levels, respectively. Data with different lowercase letters are significantly different at the 5% level.

3.2. Nitrogen Utilization

Compared with the control CK, the incorporation of biochar with reduced fertilizer significantly increased the nitrogen partial productivity and agronomic efficiency (Figure 3). Nitrogen partial productivity significantly decreased with the increase in fertilizer application. The treatment combinations of F1 had the highest nitrogen physiological efficiency (Figure 3).

Nitrogen utilization efficiency (NUE) of the control CK in 2018~2019 were 35.7% and 27.9%, respectively, and the average in the two years was 31.8%. There were no significant differences in NUE among the treatments in 2018. The NUE of all the different biochar and fertilizer treatment combinations in 2019 ranged from 41.8~61.0%, and significantly increased by 49.6~118.2% when compared to CK (Figure 3). The two year average value of the NUE of the combinations ranged from 41.5~54.2% and increased by 34.2~75.5% in average in two years.

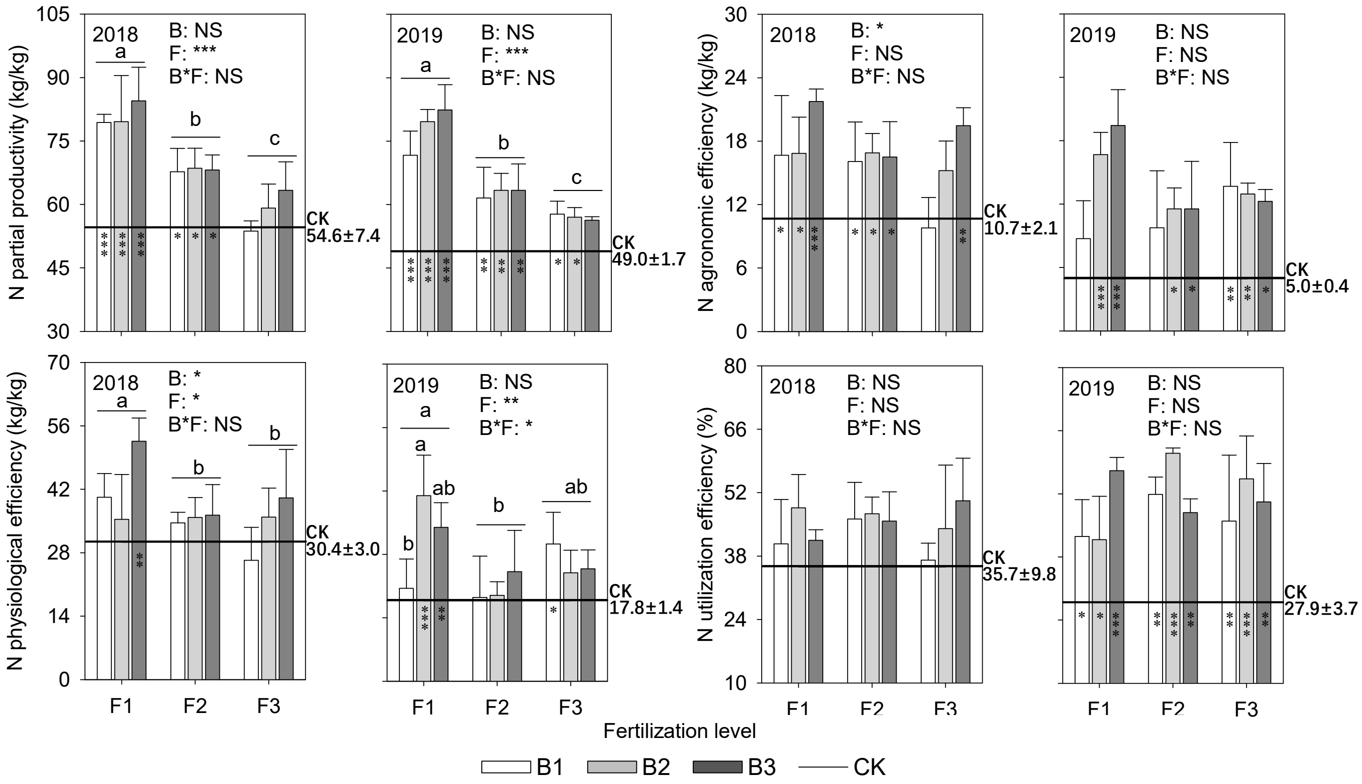

Figure 3. Nitrogen utilization efficiency of Taoyouxiangzhan (2018) and Taiyou 553 (2019) under different treatments. CK: standard doses of N-P-K without biochar application; F0: no fertilization and no biochar application; B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; B3: biochar application of 100 t/ha; F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K. Mean and standard deviation of the CK is listed beside the corresponding lines. "*", "**" and "***" indicate the significant difference between the BF combinations and the control CK at the 5%, 1%, and 0.1% levels, respectively. Data with different lowercase letters are significantly different at the 5% level.

3.3. Phosphorus Utilization

Phosphorus partial productivity was consistent with that of nitrogen, which was shown as F1 > F2 > F3 (Figure 4). Phosphorus agronomic efficiency increased with the increase of biochar application in 2018. The phosphorus agronomic efficiency of B1F1 and B1F2 had no significant differences with the control CK, and other treatment combinations were found to be significantly higher than the control CK in 2019. Phosphorus physiological efficiency was found to have increased with the increase of biochar application in 2018, and the trend with fertilizer application was F1 $\geq$ F3 $\geq$ F2; while the phosphorus physiological efficiency of B2F1, B3F1, and B1F3 were significantly higher than the control CK, and other treatment combinations had no significant differences with the control CK in 2019.

Phosphorus utilization efficiency (PUE) of the control CK in 2018~2019 was 25.5% and 35.4%, respectively, and the average in the two years was 30.4% (Figure 4). In 2018, the PUE of the F2 combinations was the highest, especially the treatments of B1F2 and B2F2, which were 53.9% and 50.9%, followed by the F1 combinations, which ranged from 34.1~41.7%. F3 combinations had lowest PUE, but B1F3 and B2F3 were found to be significantly higher than the control CK. The PUE of all the BF combinations in 2019 ranged from 55.3~64.1%, and significantly increased by 56.3~81.2% compared to the control CK (Figure 4). Compared with the control CK, the PUE of the combinations increased by 27.4~84.8% in average in two years.

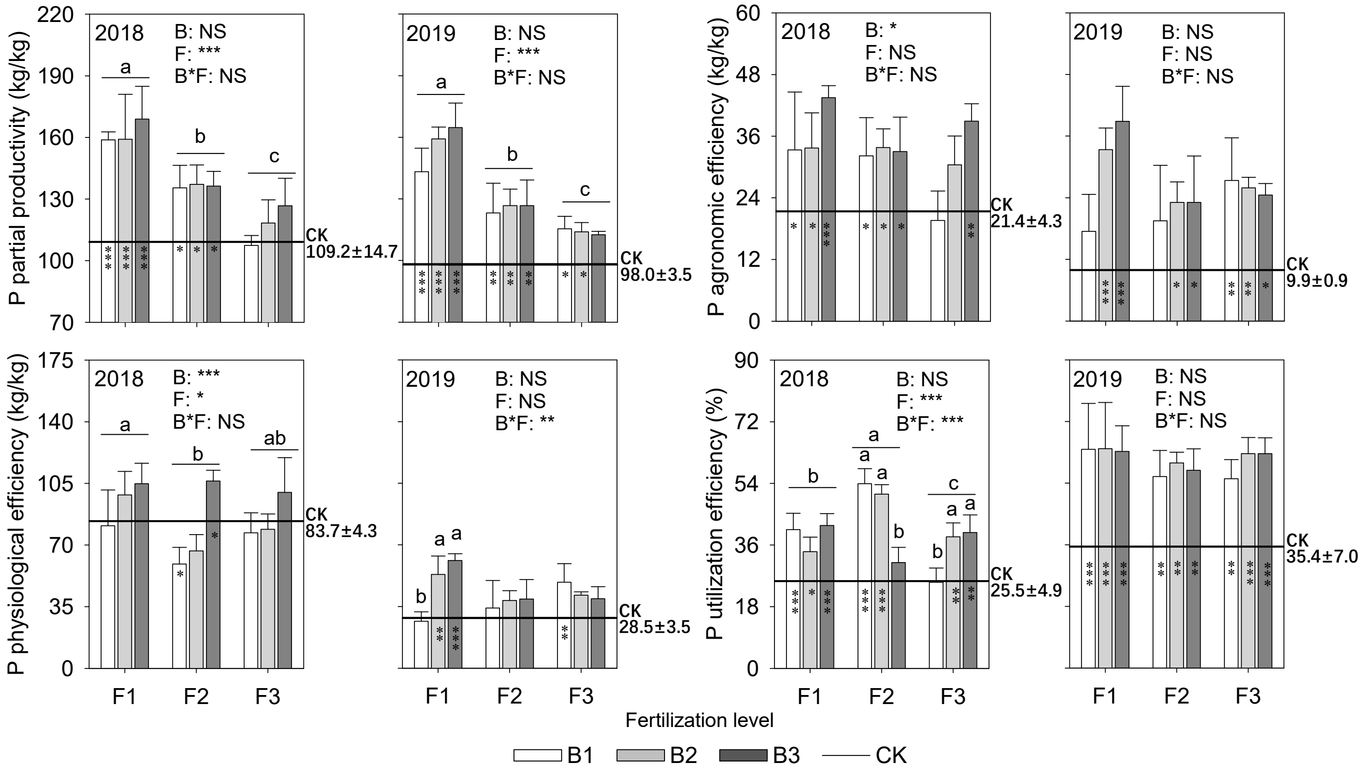

Figure 4. Phosphorus utilization efficiency of Taoyouxiangzhan (2018) and Taiyou 553 (2019) under different treatments. CK: standard doses of N-P-K without biochar application; F0: no fertilization and no biochar application; B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; B3: biochar application of 100 t/ha; F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K. Mean and standard deviation of the CK is listed beside the corresponding lines. "*", "**" and "***" indicate the significant difference between the BF combinations and the control CK at the 5%, 1% and 0.1% levels, respectively. Data with different lowercase letters are significantly different at the 5% level.

3.4. Potassium Utilization

The partial productivity and agronomic efficiency of potassium were consistent with that of N and P (Figure 5). Potassium physiological efficiency of B3F1 and B3F3 had no significant differences from that of the control CK in 2018, but other treatment combinations were determined to be significantly lower than the control CK. In 2019, the potassium physiological efficiency of the F1 combinations was the highest, particularly the treatments of B1F1 and B2F1, which were found to be significantly higher than the control CK.

Compared with the control CK, the incorporation of biochar with fertilizer significantly increased the potassium utilization efficiency (KUE) (Figure 5). KUE of the control CK in 2018~2019 was 48.5% and 44.7%, respectively, and the average for two years 46.6% (Figure 5). In 2018, the KUE of all the BF combinations ranged from 66.0~118.5%, and increased with the increase of biochar application, but decreased with the increase of fertilizer application (Figure 5). In 2019, the KUE of all the BF combinations ranged from 64.1~140.7%, which increased with the increase of biochar application and fertilizer application. The average KUE of the BF combinations ranged from 83.8~123.3%. Compared with CK, the KUE of the combinations increased by 78.52~166.70% in average in two years.

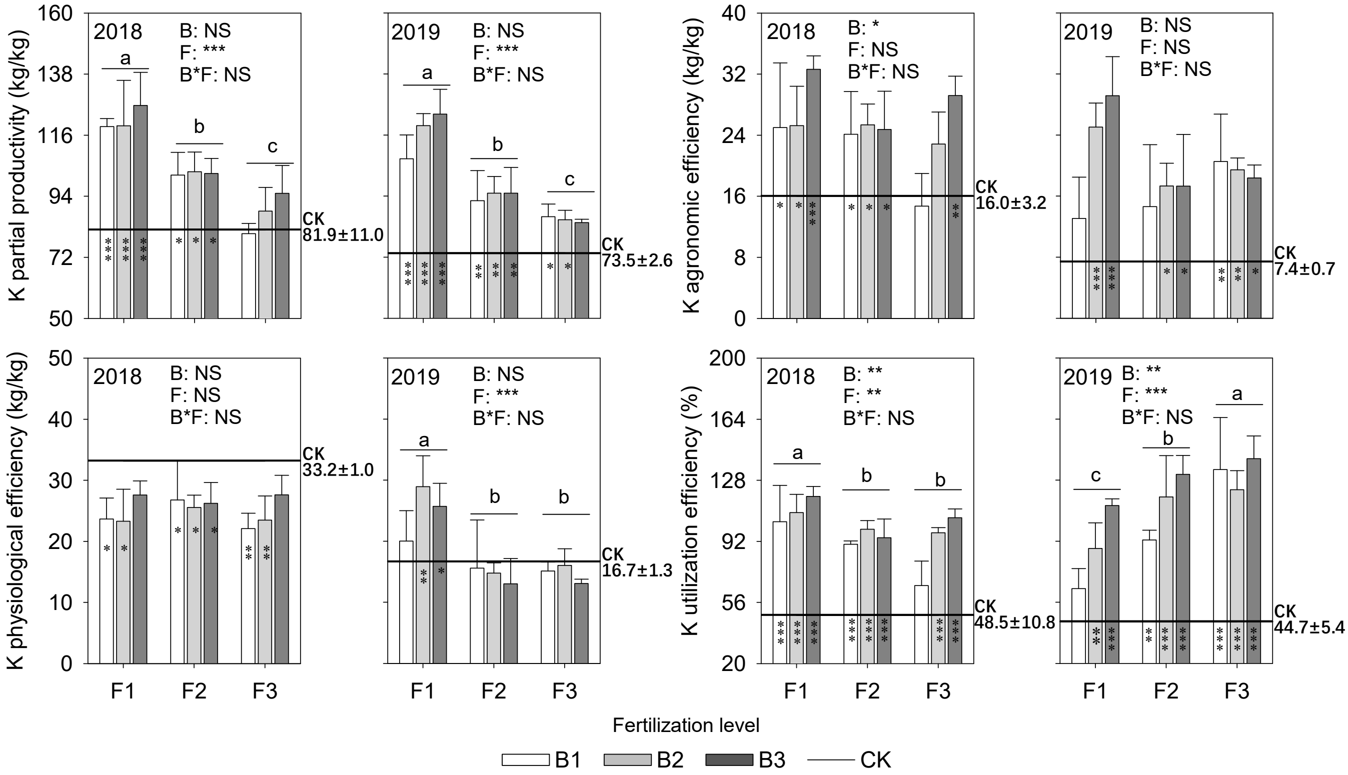

Figure 5. Potassium utilization efficiency of Taoyouxiangzhan (2018) and Taiyou 553 (2019) under different treatments. CK: standard doses of N-P-K without biochar application; F0: no fertilization and no biochar application; B1: biochar application of 60 t/ha; B2: biochar application of 80 t/ha; B3: biochar application of 100 t/ha; F1: 70% doses of N-P-K; F2: 85% doses of N-P-K; and F3: standard doses of N-P-K. Mean and standard deviation of the CK is listed beside the corresponding lines. "*", "**" and "***" indicate the significant difference between the BF combinations and the control CK at the 5%, 1% and 0.1% levels, respectively. Data with different lowercase letters are significantly different at the 5% level.

4. Discussion

Optimizing fertilization is an important way to ensure a high and stable yield of rice and reduce environmental pollution. Based on multisite studies across China, Zhuang et al. [18] found that biochar amendment had the highest average yield increasing rate and N loss-reducing rate, which is better than other optimized fertilization practices such as formula fertilization, deep fertilization, green manuring, and combined application of organic and inorganic fertilizers. Our previous five year field experiment found that grain yield was significantly enhanced with ≥60 t/ha biochar single addition in acidic paddy under standard fertilization conditions, and these effects could last for three years or more [10]. The main goal of the study was to reduce fertilizer input with biochar application under the premise of stable yield.

This study found that reduced fertilizer application had no negative effects on the grain yield after biochar application. Specifically, compared with standard fertilizer application, with biochar application, even a 30% reduced fertilizer application can ensure the stable yield of rice or increase production. This is consistent with previous observations and indicates that biochar application could partly replace fertilizer [19–21]. A meta-analysis showed that the combined applications of biochar and fertilizer significantly increased crop yield, with especially the acidic soils having the highest yield increase [22]. In the study of Zhang et al., compared with fertilization alone, combined applications of biochar and fertilizer increased grain yield by 10~16% [14]. Ning et al. found that the contribution of biochar to grain yield on the basis of a 60% dose of N was always higher than on the basis of an 80% dose of N, and indicated that the less nitrogen fertilizer applied, the greater the contribution of biochar to the grain yield [20].

Nutrient accumulation is a direct performance of nutrient absorption and utilization in rice. In this study, combined applications of biochar and reducing fertilizer significantly improved the nutrient accumulation of rice. With biochar addition, the N, P, and K accumulation of rice aboveground significantly increased under 85% doses of N-P-K and standard fertilization conditions, and had no significant change under 70% doses of N-P-K compared with CK. It indicated that moderate fertilizer reduction does not affect crop nutrient uptake, and that with biochar application, the nutrient utilization efficiency of rice was significantly improved, thereby increasing their nutrient uptake [23]. In particular, the K accumulation of rice accordingly increased with the increase of biochar application in this study. Rice is a potassium-rich plant, and the rice yield increase was significantly positively correlated with its demand for potassium [24].

Biochar application significantly enhanced the nutrient use efficiency of rice. In this study, the partial productivity of N, P, and K fertilizer increased as the fertilizer was decreased after biochar application, and the N, P, and K use efficiency under the different biochar and fertilizer combinations significantly increased by 34.24~75.48%, 27.44~84.84%, and 78.52~166.70%, respectively, compared with standard fertilization only (31.8%, 30.4%, and 46.6%, respectively). In the study of Zhang et al. [14], combined applications of biochar and fertilizer increased N and P use efficiency by 20~53% and 38~230%, respectively. With the N isotope method, Huang et al. [25] found that N uptake from fertilizer by rice increased by 23~27%, and consequently, grain yield increased by 8~10%, while fertilizer N loss rate decreased by 9~10% after biochar application. Notably, the utilization efficiency of potassium fertilizer by rice was greatly improved after biochar application. The two year average KUE of the control CK was 46.6%, and the average KUE of the BF combinations ranged from 83.8~123.3% and increased with the increase of biochar application and fertilizer application. It indicated that in terms of potassium utilization, the combined application of biochar and 70% dose of potassium fertilizer can achieve the best benefits without causing a decrease in soil potassium.

The increase in rice yield and nutrient utilization could be attributed to the complementary or synergetic effect of biochar and fertilizer [11]. Biochar application can enhance rice yield and nutrient utilization by comprehensively improving the soil environmental conditions for rice. Firstly, soil acidity is a key factor affecting soil fertility and crop yield in acidic soils. In this study, the pH value of rice husk biochar was 8.32, while the pH value of the test soil was only 5.14. Adding biochar was found to be beneficial to decline soil acidity [21,26,27], reduce phosphorus fixation, and enhance phosphorus bioavailability in acidic soil [28]. Secondly, biochar is a nutrient-rich biological material. Most of the mineral elements such as P, K, Ca, and Mg are retained in the biochar during the pyrolysis of the rice husks, which can directly provide the nutrients for rice growth [29]. Thirdly, biochar has a large specific surface area [30], rich pores, and surface functional groups [31], which are all beneficial to increase the cation exchange capacity and adsorption of N, P, K, or other effective nutrients [14], thereby improving rice nutrient utilization. In addition, biochar has a smaller bulk density and a porous structure [32] and are also conducive to improving soil physical structure [33], thereby improving soil permeability [34], reducing soil bulk density [35], promoting rice root growth, and improving root vitality [36,37].

5. Conclusions

Fertilizer reduction had no negative effects on grain yield after biochar application. When the amount of biochar added was $\geq$60 t/ha, 70% doses of fertilizer application can still ensure the nutrient absorption of rice, improve the fertilizer utilization efficiency, and ensure the stable yield of rice. Biochar can partially substitute fertilizer for rice production in the acid paddy fields of southern China. Biochar application combined with fertilizer reduction is an effective way to ensure a high and stable yield of rice and reduce environmental pollution.

Author Contributions: Conceptualization, F.C.; methodology, S.Q. and F.C.; formal analysis, S.Q.; investigation, S.Q. and F.R.; resources, L.W.; data curation, S.Q., F.R., G.S. and W.W.; writing—original draft preparation, S.Q.; writing—review and editing, F.C., M.Z., F.R. and A.W.; supervision, L.W.; project administration, F.C.; and funding acquisition, F.C. All authors have read and agreed to the published version of the manuscript.

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