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Effects of biochar on sodium ion accumulation, yield and quality of rice in saline-sodic soil of the west of Songnen plain, northeast China

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ABSTRACT

Jin F., Ran C., Anwari Q.A., Geng Y.Q., Guo L.Y., Li J.B., Han D., Zhang X.Q., Liu X., Shao X.W. (2018): Effects of biochar on sodium ion accumulation, yield and quality of rice in saline-sodic soil of the west of Songnen plain, northeast China. Plant Soil Environ., 64: 612–618.

This study evaluated the effects of biochar application on sodium ion accumulation, yield and quality of rice in saline-sodic soil by using a pot experiment. Rice was grown in the soil with no biochar, 15 g biochar per kilogram soil, 30 g biochar per kilogram soil and 45 g biochar per kilogram soil. The results indicated that biochar application significantly decreased sodium ion accumulation of rice plant parts, while it obviously increased rice dry biomass, grain yield and improved rice quality. The results suggested that biochar application to saline-sodic paddy soil has benefits to reduce stress and promote the increase of rice yield and quality formation in saline-sodic soil.

Keywords: charcoal; *Oryza sativa* L.; saline-sodic stress; absorption; physico-chemical parameters

Soil degradation resulting from salinity and/or sodicity is a major environmental barrier with severe adverse impacts on agricultural productivity and sustainability in arid and semiarid climates. These soils possess a number of challenges that include poor physical and chemical properties that affect the growth of most crops. The Songnen Plain, located between 42°30'–51°20'N and 121°40'–128°30'E, is the largest plain in northeast China. The west side of this plain is one of the five largest salt-affected soil regions in China (Yu and Cheng 1991). The area of salt-affected soil, 0.5% to 1.0% total salts, encompasses 3.42×10^6 ha, which accounts for over 19.0% of the total area (Song et al. 2003, Wang et al. 2003). The inhibitory effects of saline-alkali on plants are mainly due to the ion toxicity, osmotic effect and high pH stress (Al-Karaki 1997, Chi et al. 2012). These can cause nutritional disorders and reduce soil water potential, limit the uptake of essential plant nutrients (K, Ca, Mg, P etc.) and water, hinder root respiration, hence reducing plant growth and activity of soil organisms and ultimately result in crop yield losses (Chaganti and Crohn 2015). To better utilize these saline-sodic soils, rice (*Oryza sativa* L.) was planted in this plain because the flooded water not only is beneficial to its growth but also is necessary for leaching salts (Li et al. 2006, Chi et al. 2012). However, with the global climate change and environmental pollution aggravating, the ecosystems of saline-sodic soils are facing serious problems such as soil barren, low utilization rate of fertilizer, increasingly serious salinization degree and water shortages.

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These problems lead to the extreme imbalance of ecological environment in saline-sodic soil area, to serious threat to the development of rice production and limiting the sustainable development of saline-sodic soil.

Biochar is like organic matter that can effectively reduce the absorption of crops to Na^+, reduce the salinity stress to crops (Thomas et al. 2013, Yang et al. 2014), supply minerals nutrients, increase soil organic carbon, cation exchange capacity and to better plant growth (Akhtar et al. 2015, Chaganti and Crohn 2015). Biochar is favourable to optimize root morphology and physiological characteristics in rice and increases rice yield significantly; this effect of biochar on crop yield has also been increased with time (Steiner et al. 2008, Zhang et al. 2013). Research about the beneficial effects of biochar has mostly focused on low latitude area, tropical soils or on soil physico-chemical parameters and dry crop. There are a limited number of reports describing the effects of biochar on rice grown in saline-sodic paddy soil. Therefore, the aim of this study was to assess the effects of biochar on yield, quality and sodium ion accumulation of different rice plant parts in saline-sodic paddy soil. It is anticipated that the study results will be useful for formulating novel management ways for improving crop production on saline-sodic soil.

MATERIAL AND METHODS

Soil sampling and analysis. Samples of saline-sodic paddy soil were collected from paddy soil area near the Da'an Sodic Land Experimental Station (45°35'58''–45°36'28''N, 123°50'27''–123°51'31''E) operated by the Chinese Academy of Sciences in the Songnen Plain. The area has a temperate zone continental monsoon climate. The annual mean air temperature is 4.7°C, and the average annual precipitation is 413.7 mm. The annual mean evaporation is 1696.9 mm. These soils had a history of planting rice for four years and had clay loam texture according to the USDA texture classification system. The main soil type is a Solonetz based on the World Reference Base for Soil Resources (IUSS Working Group 2014). Random soil samples were collected from 0 cm to 25 cm depth. Approximately 1000 kg of soil samples was collected. These samples were air-dried and then passed through a 2-mm sieve.

The soil basic characteristics including salinity, sodicity, pH, sand content, silt content, clay content and organic matter were measured before application of the test. Soil texture was determined by the hydrometer method (Gavlak et al. 2003). Soil pH and cation exchange capacity (EC) were measured in saturated paste and saturated paste extract by the method of Richards (1954) using EL20 pH meter (Mettler Toledo International Trade Co. Ltd, Shanghai, China) and DDS-307 conductivity meter (Shanghai Precision Scientific Instrument Co., Ltd, Shanghai, China), respectively. Soluble base cations (Ca^{2+} and Mg^{2+}) were also quantified using the same extracts by inductively coupled plasma optical emission spectrophotometry (PerkinElmer Optima 7300V ICP, Perkin Elmer enterprise management Co. Ltd, Norwalk, USA), Na^+ and K^+ were determined using the flame photometer (M410 Sherwood, Cambridge, UK). Sodium adsorption ratio (SAR) was calculated by the following Eq. (1):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (1)$$

Where: Na^+, Ca^{2+} and Mg^{2+} – respective soluble cation concentrations given in mg/kg. Soil cation exchange capacity was quantified using the Bower saturation method given by Richards (1954). Soil extractable cations were determined by rinsing soils for 10 min with 1 mol/L ammonium acetate solution buffered at pH 8.5. Exchangeable cations were measured as the difference between the extractable and soluble cations. Exchangeable sodium percentage was calculated using Eq. (2):

$$ESP\ (\%) = \frac{\text{Exchangeable Na}}{\text{CEC}} \times 100 \quad (2)$$

Soil organic matter content was determined using the loss on ignition method (Gavlak et al. 2003). Important soil physicochemical properties are presented in Table 1.

Production and properties of biochar. Biochar used for the test experiment was produced from wheat straw by the Jinhefu Agricultural development Co. Ltd, Liaoning, China. The biochar was produced by pyrolysis of the wheat straw at 350–550°C. For the test study, the biochar mass was ground to pass through a 2 mm sieve, and mixed thoroughly to obtain a uniform powder that would mix more uniformly with the soil. Following the protocol described by Lu (2000), the biochar properties were characterized for total organic C and N with an Elementar Vario max CNS Analyser

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Table 1. Physicochemical properties of the soil

Soil characteristic	Value
Sand content (%)	22.13
Silt content (%)	37.14
Clay content (%)	35.60
Bulk density (g/cm)	1.38
Cation exchange capacity (uS/m)	23.91
pH	8.53
Sodium adsorption ratio $(mmol_{+}/L)^{1/2}$	352.11
Exchangeable sodium percentage (%)	71.11
Organic carbon (%)	0.50

(German Elementar Company 2003, Hanau, German). The pH of biochar was measured for a 1:5 biochar/water suspension with a compound glass electrode (Mettler Toledo International Trade Co. Ltd, Shanghai, China). The mineral element content was determined by acid digestion and elemental analysis followed by atomic adsorption spectroscopy (GBC-906AAS, Australia Science instruments Co. Ltd, Melbourne, Australia). Basic properties of biochar are presented in Table 2.

Pot experiment. The experiment was conducted in a greenhouse under controlled conditions at the experimental farm. Sixty plastic pots (35 cm length, 29 cm internal diameter) were used to prepare the soil and each pot could hold up 7.5 kg of test soil. The soil samples were treated with four alternative treatments. Non-biochar pots served as a control (CK), pots with 15 g, 30 g and 45 g of biochar added per kilogram of soil served as T1, T2 and T3, respectively. Each treatment was replicated three times. Rice seeds cultivar (G9) were selected as experimental type and were initially plug in trays containing compost in an unheated glasshouse. Forty-day-old seedlings were transplanted on May 20, 2016 into each plastic pot. Three seedlings (three hills per pot, one seedling per hill) were transplanted into each pot. A fertilizer containing 15% N, 25% P and 5% K (Sino-Arab Chemical Fertilizers Co. Ltd, Qinhuangdao, China) was applied to each column to ensure that nutrient supply was non-limiting for the first month. Irrigation water used was collected from underground water and this water was reclaimed by water purifier. Relevant chemical properties of the reclaimed water are listed in Table 3.

Table 2. Basic properties of biochar

pH and elemental component (mg/g)	Peanut shell	
	raw material	biochar
pH	5.56	7.94
C	429.19	440.64
N	10.85	15.93
S	2.58	6.85
Mg	1.46	0.25
K	5.51	12.53
Ca	6.32	2.01
Fe	2.77	2.07
Be	0.14	13.41
Mn	0.09	0.06
Ni	0.00	0.00
Cu	0.01	0.01
Zn	0.02	0.15
B	0.02	0.01

Rice yield, quality and sodium ion accumulation analysis. In the physiological mature stage (grain hard, difficult to divide with thumbnail), rice plants of 15 pots were harvested for each treatment. The above biomass was divided into stem, leaf, sheath and panicle. These samples were dried at 105°C for 30 min and then adjusted to 80°C until constant weight and dry weights were measured. The content of Na^{+} was determined by the flame meter method (M410 Sherwood, Cambridge, UK).

In the mature stage (grain very hard, cannot be dented by thumbnail), 25 pots were used per treatment to determine the yield of single plant and yield components. The mature crop was harvested by cutting at soil level. The numbers of panicles per hill, spikelets per panicle, seed setting rate, 1000-grain weight and grain yield of per hill were recorded.

Mature rice grains were milled after harvest, air dried and stored at room temperature for 3 months. A total of 20 pots were harvested from each treatment. The brown rice ratio, milled rice ratio, and head rice ratio were calculated after harvest. The grains were dehulled to produce brown rice using

Table 3. Relevant chemical properties of the reclaimed water

Characteristic		Mean value
pH		7.2
Mg	(mg/L)	2.9
K	(mg/L)	2.2
Ca	(mg/L)	3.9
Na	(mg/L)	2.77

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the Rubber Roll Sheller (THU Testing Hunsker, Satake, Hiroshima, Japan), and brown rice ratio was determined. Thereafter, the brown rice was milled with rice-polishing machine (TM05 test mill, Satake, Saitama, Japan). After milling, head rice and broken rice were separated and finally, the milled rice ratio and head rice ratio were expressed as percentage of total weight of rough rice. The chalky percentage, chalkiness ratio, length-width ratio and amylose content were assessed according to the National Standard of the People's Republic of China (GB/17891-1999). Measurements of rice protein content were performed as described by Li (2000) and Tan et al. (1999). All samples were analysed twice.

Statistical analysis. The experiment was conducted in a completely randomized design in the greenhouse. The combined effects of salinity and biochar were analysed using a two-way ANOVA. The Tukey's test was applied as post-ANOVA test at the 5% level of significance. Regression analyses between some of the variables were made on the data across all treatments. All analyses were done with the SPSS18.0 software (New York, USA).

RESULTS AND DISCUSSION

Effects of biochar on Na^+ accumulation of rice. The sodium ion accumulation at the stem, leaf, sheath and panicle of rice in saline-sodic soil were significantly decreased by adding biochar and decreased with the addition rate of biochar application. The

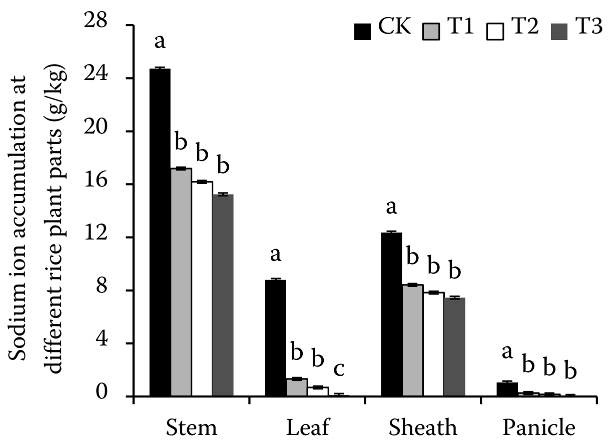

Figure 1. Effects of biochar application on sodium ion accumulation at different rice plant parts. T1 – 15 g, T2 – 30 g, T3 – 45 g of biochar per kilogram of soil; CK – non-biochar

sodium ion accumulation in different rice parts under biochar adding treatment was significantly different with CK ($P \leq 0.05$). However, the differences between biochar addition treatments were not significant (Figure 1). Thus, it can be concluded that biochar application in saline-sodic soil could significantly reduce sodium ion accumulation at different rice plant parts. Biochar addition reduced plant sodium uptake and reduction of the salinity stress to crops has been previously reported by other authors such as Chaganti and Crohn (2015). Biochar addition reduced plant sodium uptake under salt stress soil by transient Na^+ binding due to its high adsorption capacity and by releasing mineral nutrients (particularly K^+, Ca^{2+}, Mg^{2+}) into the soil solution (Akhtar et al. 2015, Melas et al. 2017). Novak et al. (2009) reported that biochar can effectively decrease the absorption of plant to Na^+, significantly decrease sodium ion accumulation and reduce osmotic stress and Na ion toxicity for better plant growth in salt soil.

Effects of biochar on dry biomass and yield of rice. There was a positive effect of biochar treatments on dry biomass accumulation and yield of rice in saline-sodic paddy soil (Table 4). Dry biomass of stem, leaf, sheath, panicle and the total biomass showed a trend of T2 > T3 > T1 > CK, the total biomass of T1, T3 and T2 were increased by 13.08, 23.31 and 29.25% respectively compared with CK, and the difference between biochar treatments and CK reached a significant level ($P \leq 0.05$). The difference between T2 and T1, CK was significant ($P \leq 0.05$), while the difference between T1 and T3 was not significant. These results are in agreement with the work of Abrishamkesh et al. (2015), who reported that the

Table 4. Effect of biochar application on rice dry biomass in different rice plant parts

	Mature stage (g/hill)			
	CK	T1	T2	T3
Leaf	9.05^{b}	9.80^{ab}	10.95^{a}	10.60^{a}
Sheath	15.35^{c}	16.35^{b}	18.10^{a}	17.70^{ab}
Stem	16.30^{b}	18.01^{a}	19.55^{a}	18.05^{a}
Panicle	43.05^{c}	51.22^{b}	60.60^{a}	56.91^{a}
Total	84.35^{c}	95.38^{b}	109.02^{a}	104.01^{ab}

Values within a column followed by different letters are significantly different at 0.05 probability level. T1 – 15 g, T2 – 30 g, T3 – 45 g of biochar per kilogram of soil; CK – non-biochar

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yields of crop were affected positively with biochar amendment under high salinity level.

Through analysis of the grain yield it was indicated that the grain yield of biochar application treatments had significantly increased compared with CK ($P \leq 0.05$), T1, T2 and T3 were increased by 10.59, 15.81 and 13.79%, respectively compared with CK, and the average increase was 13.4% (Figure 2). The T2 resulted in the highest grain yield, the difference between T2, T3 and T1 was significant, but between T2 and T3 it was not significant.

Among the yield components (Figure 2), all the yield components of biochar application treatments were higher than CK in saline-sodic soil. The number of panicle per hill and spikelets per panicle of rice were significantly increased after biochar application, and generally showed a trend as T2 > T3 > T1 > CK; the biochar treatments were significantly increased compared with CK ($P \leq 0.05$). The setting percentage of rice also showed increased trend as T2 > T3 > T1 > CK after biochar application, significant difference was found in T2, but not in T1 and T3. Hence, the increase of the number of panicle per hill, spikelets per panicle and setting percentage were the main factors for the grain yield rise.

The role of biochar in improving soil quality, crop rhizospheric environment and increasing crop yields were previously reported (Lehmann et al. 2011, Chen et al. 2015). Biochar is known to modify soil physicochemical parameters (Lehmann et al. 2011), which can affect root biomass and optimize root morphology and physiological characteristics, and then increase the rice yield (Zhang et al. 2013, Abrishamkesh et al. 2015). Biochar application can effectively displace Na^+ from soil-salts and then discharges of it, decrease the osmotic stress by increasing the adsorption of water and supplying minerals nutrients i.e., K^+, Ca^{2+}, Mg^{2+} and so on, which can promote crops development and growth and increase crops yield (Akhtar et al. 2015). Liu and Zhang (2012) reported that alkaline biochar did not increase the pH of five types of alkaline soils, but instead produced a decreasing pH trend, which can reduce the effect of high pH on the growth and development of rice and soil nutrient availability. Figure 1 showed that the sodium ion accumulation significantly decreased and reduced sodium ion toxicity for better rice growth and yield formation after biochar applied in saline-sodic paddy soil. Biochar can effectively enhance the absorption ability of the soil for the nutrients such as NH_4^+, P^+, K^+ and Mg^{2+} and prevent them from leaching or volatilization loss, thus facilitating nutrients absorption and slowdown their release and improving the utilization efficiency and yield formation of crops (Liang et al. 2014, Nguyen et al. 2017).

Effects of biochar on rice quality. The rice quality was significantly improved after biochar application in saline-sodic paddy soil, and the effect of T2 on rice quality was higher than that of other treatments (Figure 3). The brown rice ratio (Figure 3a), milled rice ratio (Figure 3b) and head rice ratio (Figure 3c) of biochar applied treatments

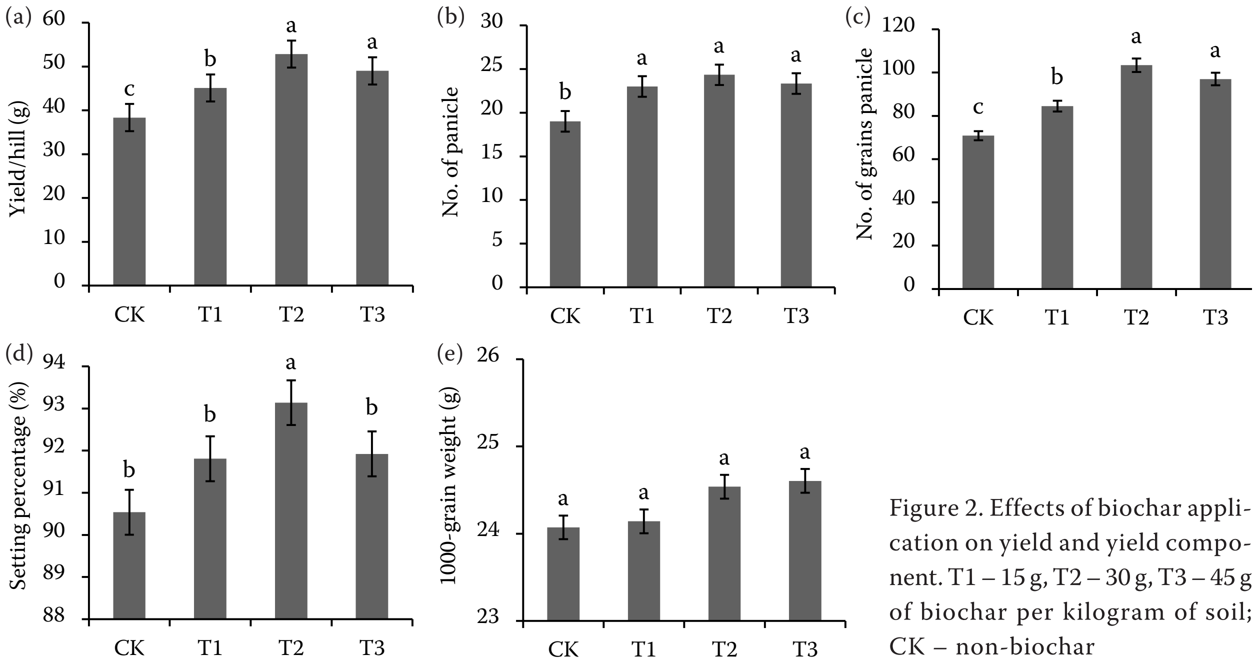

Figure 2. Effects of biochar application on yield and yield component. T1 – 15 g, T2 – 30 g, T3 – 45 g of biochar per kilogram of soil; CK – non-biochar

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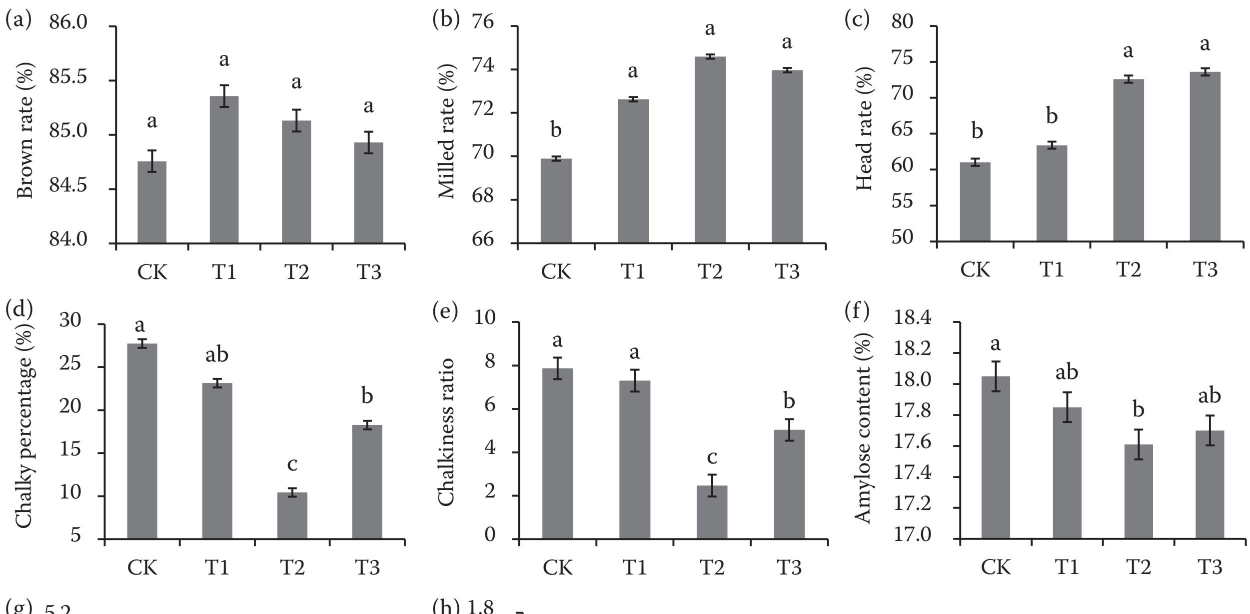
were significantly higher than CK. Among them, brown rice rate of T1 was the highest, T2 took the second place, but no significant difference was found among the treatments; the milled rice ratio showed T2 > T3 > T1 > CK, a significant difference was found with biochar application compared with CK, but no significant difference was found among biochar application treatments; head rice ratio showed the trend as T3 > T2 > T1 > CK; at T3 and T2 significant differences were found compared with CK, but no significant difference was found between T1 and CK. The chalky percentage (Figure 3d) and chalkiness ratio (Figure 3e) was improved after biochar application, T2 was the lowest and CK was the highest, significant differences were found between CK and T2, T3. The length-width ratio (Figure 3h) of biochar application treatments was significantly higher than CK. The amylose content (Figure 3f) showed a downward trend as T2 < T3 < T1 < CK; a significant difference was found between T2 and CK; the protein content (Figure 3g) significantly decreased after biochar application in saline-sodic paddy soil, and it resulted as T2 < T3 < T1 < CK, Thus, it can be concluded that the rice taste was also improved to some extent. As described above, biochar is known to modify soil physico-chemical parameters, optimize rhizospheric environment and eliminate saline-alkali stress, and increase the rice yield (Zhang et al. 2013, Abrishamkesh et al. 2015). In this study, it was also found that adding biochar could effectively reduce the absorption of Na^+ in different rice plant parts, which could promote rice growth, grain filling and thus be beneficial to the formation and improvement of rice quality. However, little is known about the effect of biochar application on rice quality, especially in the saline-sodic soil at present, and the results of our study are worthy further exploitation.

In conclusion, biochar has positive effects on rice growth in saline-sodic soil. A positive effect of biochar application on Na^+ accumulation of rice organs was shown as sodium ion stress and osmotic stress on rice decreased. Our results also showed that dry biomass, grain yield, number of panicle per hill and spikelets per panicle of rice were significantly increased after biochar application. Moreover, the rice quality was significantly improved by using biochar in saline-sodic soil. Based on the results of the lowest Na^+ accumulation



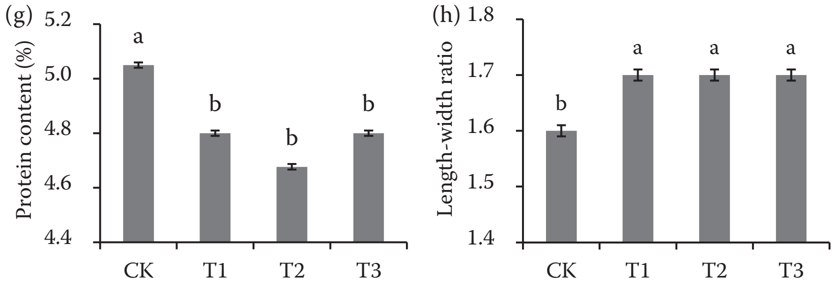


Figure 3. Effects of biochar application on rice quality. T1 – 15 g, T2 – 30 g, T3 – 45 g of biochar per kilogram of soil; CK – non-biochar

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in rice parts, higher grain yield and quality, T2 is the most optimal rate applied in saline-sodic soil.

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