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Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain

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ABSTRACT

Salt stress has been one of the extreme conditions threatening world crop production which may become more serious under climate change. This study is to address the potential of using biochar as an organic matter-rich material to ameliorate salt stressed soil in order to enhance crop production in dry croplands. A two year field experiment with soil amendment of biochar poultry manure compost (BPC) and pyroligneous solution (PS) was conducted in a moderately salt stressed Entisol from Central China. The soil was amended with BPC at 12 t ha^{-1} following treatment with diluted PS solution at 0.15 t ha^{-1} 1 week before winter wheat sowing. Samples of topsoil and plant were collected while the yield was measured when harvested. The changes in soil salinity, fertility properties as well as crop yield were examined with comparison between the plots treated for one year and for two years. In the first cropping year of 2010–2011, a significant decreases under BPC-PS amendment was observed in soil salinity by 3.6 g kg^{-1}, soil pH by 0.3 and in soil bulk density by 0.1 g cm^{-3} while increase was seen in SOC and available phosphorous by 2.6 g kg^{-1} and by 27 mg kg^{-1} respectively. The yield was increased over the control by several folds and by 38% under BPC-PS treatment respectively for 1 year and for 2 years. Furthermore, the decrease in soil salinity, soil pH, and bulk density was even greater in the plots treated for 2 years than for one year though the yield under the treatment was not significantly different between the consecutive two years with a spring drought in 2012. These results demonstrated a strong effect of BPC-PS treatment on salinity reduction and crop productivity enhancement in the salt stressed soil, which could sustain for at least two years. Therefore, biochar amendment of biochar compost in conjunction with pyroligneous solution from wheat straw could be an effective option to alleviate the salt stress and improving crop productivity in salt affected croplands.

1. Introduction

Due to its negative effects on microbial activity and soil physical properties, soil salinity poses a major threat to soil productivity in arable croplands (Kang et al., 2005; Masoud and Koike, 2006; Lobell et al., 2007) and salinization has become a worldwide problem restricting global crop production and food quality (Kammann et al., 2011). Salt-affected croplands are still extending due to poor water resources and unfavorable irrigation in the countries of Australia, Pakistan, China and Indonesia (Metternicht and Zinck, 2003; Zhang, 2005; Li et al., 2007; Ren et al., 2007). Projects with water conservation, proper irrigation and drainage, shifting rice planting have been developed for preventing extension of saline-alkaline soil (Abbasi et al., 2011) while chemical amendments of plaster, gypsum as well as organic materials have been practiced with depressing salinity in croplands in many countries (Amezketa, 2006). China's agriculture is facing a great challenge of sustaining crop production with the increasing drought and soil salinization risk in the agricultural region of North China due to the climate change (Pan et al., 2011a,b). Reclamation of salt-affected croplands and prevention of soil salinization has been urged in China's agriculture (Wang et al., 2008; Fan et al., 2011). Proper and cost-effective measures for depressing salt stresses on crop growth have thus been a priority need in technology development in China's agriculture (Yu and Wang, 1997; Guan, 2008; Yu et al., 2009; Li et al., 2010).

Abbreviations: BPC, biochar poultry manure compost; PS, pyroligneous solution; BD, soil bulk density; SOC, soil organic carbon; CEC, cation exchange capacity; WPT, weight per thousand grains.

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Table 1
Basic properties of the original topsoil (0–20 cm), biochar and pyroligneous solution and biochar poultry manure compost used for the experiment.

Sample	pH (H_2O)	TOC ($g\,kg^{-1}$)	Total N ($g\,kg^{-1}$)	Salt ($g\,kg^{-1}$)	CEC ($cmol\,kg^{-1}$)	Bulk density ($g\,cm^{-3}$)
Topsoil	8.25	5.13	0.70	12.68	21.26	1.33
Biochar	10.35	467.20	5.90	41.97	21.70	0.65
PS	9.37	3.87	0.55	/	/	1.00
BPC	7.50	419.7	25.03	/	/	/

TOC total organic carbon; CEC cation exchange capacity.

Biochar (BC) is a carbon-rich material produced via pyrolysis of biomass with limited oxygen (Lehmann and Joseph, 2009). Biochar soil amendment (BSA) has been widely shown its beneficial role in increasing crop yield as biochar improves soil structure reportedly due to its effects on bulk density, pore-size distribution and particle size distribution (Lehmann and Joseph, 2009; Sohi et al., 2009). With BSA, beneficial biophysical effects could be expected on the availability of air and water within the root zone and in turn on the germination and survival of plants (Lehmann and Rhodon, 2006a; Zhang et al., 2011). The role of BSA in increasing soil carbon storage and mitigating N_2O emissions from croplands has been well addressed globally for the last decade (Glaser et al., 2002; Mann, 2002; Lehmann et al., 2006b; Marris, 2006; Yamato et al., 2006; Lehmann, 2007; Chan et al., 2007, 2008). While BSA has been proposed for restoration of desertified (Bai et al., 2008) and secondary salinized land (Li et al., 2007; Lehmann and Joseph, 2009), there has been few field studies on the effects of biochar amendment on salt affected croplands.

Pyroligneous solution (PS), a large volume by-product when biochar is produced via pyrolysis of crop straw (Pan et al., 2010) and it has been widely recognized as a potential soil amendment in agriculture (Pangnakorn et al., 2009). It has been reported that PS can improve soil quality, depress impact of pests and plant disease (Pangnakorn et al., 2011), and benefit crop growth as a plant growth regulator or weed inhibitor (Apai and Thongdeethae, 2001). In the PS released from crop straw when pyrolyzed, up to 200 chemical substances have been identified (Mun and Ku, 2010) with the major organic substances of organic acids, phenolic substances, carbon substances, alcohol, neutral materials, and base acidic substances (Yan et al., 2011). Accordingly, PS could have influence on leaching soluble salts from soil and decreasing soil pH, thus benefiting crop production in salt-affected cropland. As technologies of biochar production from crop straw with pyrolysis have been well developed in China for the last years (Pan et al., 2010), commercialization of biochar products and its potential to use for saline soil reclamation has to be addressed.

In this study, therefore, we hypothesize that amendment of biochar poultry manure compost in adjunction with pyroligneous solution (BPC-PS) could alleviate the salt stress and improve crop productivity through improving soil physical and biological properties while neutralizing soil reaction and enhancing salt leaching in salt affected cropland. We performed a two year field experiment with amendment of biochar poultry manure compost (BPC) in conjunction with PS in a moderately salt affected cropland and looked at effects on soil and crop salinity as well as wheat yield for developing saline soil reclamation technology.

2. Materials and methods

2.1. Experiment site and soil

The field experiment site was located in Kangzhuang Village (34°32′N, 115°30′E), Xieji Township, Liangyuan District, Shangqiu Municipality, Henan province, China. The site lies on the Central Great Plain of North China. The area is governed by a semi-humid/arid temperate monsoon climate. The mean annual temperature was 13.9 °C with accumulated temperature over 10 °C being 4800 °C per year. The annual precipitation from was 690 mm and 780 mm respectively for July 2010 to June 2011 and from July 2011 to June 2012. The mean annual potential evaporation was 1735 mm for the period of 2008–2012. The total sunshine time per year amounted to 2510 h, and annual frost-free days per year reached 230d. The soil was an Aqui-Entisol following Chinese Soil Taxonomy (Gong, 1999), which derived from paleo-alluvial sediments of the Yellow River. The soil was slightly alkaline, poor in organic carbon and soil nutrients, moderately compacted despite a high cation exchange capacity (Table 1). As a local conventional cropping system, cultivation of summer maize, winter wheat had been rotated since 1980s' in the region.

2.2. Biochar and pyroligneous solution used

Biochar used for the field experiment was produced with pyrolysis of wheat straw at 350–550 °C in a vertical kiln from the Shangqiu Sanli New Energy Company, China. With the technology developed by the company, one ton of wheat straw dry matter was converted to 300 kg of biochar plus 250 L of PS as a by-product (Pan et al., 2011a,b). The basic property of biochar and the chemical composition of PS were reported respectively by Zhang et al. (2010, 2011) and by Yan et al. (2011). Prior to use, biochar material was ground to pass a 2 mm sieve and homogenized thoroughly and the PS was diluted 5-folds using distilled water.

2.3. Biochar poultry manure compost (BPC)

For developing biochar manure compost, poultry manure was collected from a local poultry farm and laid in open air storage for 1week under ambient condition for losing extra amount of moisture. Then the poultry manure (PM) was mixed with the biochar material (BC) in a ratio of 1:3 (PM:BC, v/v) for composting for 6 weeks. The produced BPC was thoroughly mixed prior to soil amendment. The compost is a dark loose neutral (pH in water 7.5) organic material containing 419.70 $g\,kg^{-1}$ of organic carbon, 25.03 $g\,kg^{-1}$ of total N, and 0.82 $g\,kg^{-1}$ of alkaline-releasable N, 12.20 $mg\,kg^{-1}$ of Olsen-P and 0.83 $mg\,kg^{-1}$ of NH_4NO_3 exchangeable K as well.

2.4. Experiment design

In this study, an abandoned salt-affected soil was used for field experiment. A plot was treated with combined amendment of BPC-PS. Diluted PS at 0.15 $t\,ha^{-1}$ was directly sprayed on soil surface one week before BPC was broadcasted on soil surface at 12 $t\,ha^{-1}$ 1 week before direct wheat sowing. The broadcasted BPC was thoroughly mixed with the topsoil by machinery plowing to a depth of 20 cm and then machinery raked for leveling. Following the local conventional fertilization, basal fertilizers of urea, calcium super-phosphate and potassium chloride was applied at 112.5 $kg\,N\,ha^{-1}$, 112.5 $kg\,P_2O_5\,ha^{-1}$ and 112.5 $kg\,K_2O\,ha^{-1}$, respectively. Seeds of Bainong Aikang 58, a region-typical cultivar of winter wheat, were directly sowed on 15th October, 2010. At the jointing stage, 120 $kg\,N\,ha^{-1}$ as urea was additionally ditch-applied as supplementary fertilizer to depth of 10–15 cm in the row and covered by the soil.

For comparison, we used a plot of unreclaimed salt-affected as background control (CK0), which was similarly fertilized and plowed but without BPC-PS. The wheat cultivar and use of chemical fertilizers under CK0 were the same as the BPC-PS treatment. As conventional in the region, crop straw was mostly returned by crashing and plowing into the plow year after harvest.

The experiment was repeated for duration of the treatment effects in 2011. For this, a new plot (BPC-1, hereafter) was treated with the same procedure as in 2010. And the plots treated in 2010 were amended no more with BPC but with only PS in same dosage before wheat sowing in 2011 (BPC-2). The same plot of control was used for comparison in 2012(CK1, here after). By this design, the ongoing effect of BPC treatment can be addressed in terms of variation with years.

The experiment was repeated in triplicates with a complete randomized block design of the individual plots in an area of 0.15 ha. The crop growth management was consistent across the treated and untreated plots. No irrigation was performed during wheat production.

2.5. Soil sampling and analysis

For soil fertility assessment, topsoil sampling was done after wheat harvest in late May both of 2011 and 2012. A composite sample at depth of 0–20 cm was obtained of 5 subsamples collected using an Eijkelkamp core sampler in an *S*-shaped pattern from each treatment plot. Samples were sealed in plastic bags then shipped to the laboratory within 24 h after sampling. Visible plant detritus, gravels were removed from the samples before air-drying at room temperature. One portion of a sample was ground to pass a 2 mm sieve and a portion of which was further ground to pass a 0.15 mm sieve for chemical analysis. Basic soil properties were determined following the conventional laboratory protocols described by Lu (2000). Soil pH (H_2O) was measured by Metter-Toledo pH meter with soil: water ratio of 1:2.5. Cation exchange capacity (CEC) was measured with ammonium acetate (1 mol L^{-1}, pH 8.7) leaching method; total soil salt contents was measured with water extraction and weighed after completely oven-dried. Soil bulk density (BD) was measured using a cylinder of 100 cm^3 in volume with 7 random replicates collected in a plot.

2.6. Wheat yield measurement

Wheat was harvested and grains were threshed using a thresher and weighed to obtain a yield separately for each experiment plot.

2.7. Statistical analysis

All analytical data were expressed as mean plus/minus one standard deviation. Data processing was performed with Microsoft Excel 2003 Statistical analysis was done with SPSS, version 16.0 (SPSS Institute, USA, 2001). Significance for differences between the treatment means was examined by one-way analysis of variance (ANOVA), with a probability defined at 0.05.

3. Results

3.1. Soil physical and chemical property

Data of measurements of soil salinity changes including pH and salt content under the treatments are organized in Table 2. A significant decrease was clearly seen in soil pH (H_2O), salt and sodium content in BPC-PS treated plot over the untreated plot (CK0). Compared to CK0, BPC-PS treatment reduced the soil pH (H_2O) by 0.3, soil BD by 0.1 g cm^{-3} and salt content by 3.6 g kg^{-1} (from 9.21 g kg^{-1} to 5.63 g kg^{-1}) in the experiment of first crop year of 2010–2011. In the subsequent crop year of 2011–2012, soil pH was decreased compared to CK1 by 0.14, soil BD by 0.16, total salt content by 3.42 g kg^{-1}, and exchangeable Na^+ by 2.14 g kg^{-1} under BPC applied in 2010 (BPC-2). Accordingly, significant decreases under BPC-PS treatment in soil pH, bulk density and salinity were found consistent across the two cropping years when comparing BPC-2 to both CK1 and BPC-1.

Table 2
Salinity of topsoil (0–20 cm) under BPC-PS treatment of the salt-stressed soil.

Crop year	Treatment	pH (H_2O)	Salt (g kg^{-1})	Na^+ (g kg^{-1})
2010–2011	CK0	8.23 ± 0.06a	9.21 ± 0.39a	5.62 ± 0.22a
	BPC	7.94 ± 0.02b	5.63 ± 0.55b	3.69 ± 0.04b
2011–2012	CK1	7.83 ± 0.13ab	8.46 ± 0.41a	5.53 ± 0.13a
	BPC-1	8.00 ± 0.13a	5.57 ± 0.18b	3.66 ± 0.06b
	BPC-2	7.69 ± 0.05b	5.04 ± 0.17b	3.39 ± 0.06c

Different letters in a same column indicate significant differences ($p < 0.05$) between the treatments in a single year.

3.2. Soil nutrient status

In Table 3 the data of topsoil fertility parameters under different treatments are presented. There were significantly higher SOC and available P as well as lower BD in the BPC-PS amended plots than in the control plot though CEC was not changed. Under BPC-PS amendment in the first year, SOC and available P were greatly increased by 2.6 g kg^{-1} and by 26.95 mg kg^{-1} respectively over CK0. Total N content was seen not significantly different between the treatments, in a narrow range of 0.78–0.84 g kg^{-1} for all the treatments in the first cropping year. In the second cropping year, SOC, total nitrogen, available K and available P of BPC-2 plots was found increased by 49%, 69%, 78% and 25% respectively over CK1. While the SOC and other soil nutrients in BPC-2 plots were high than in BPC-1 plots, increased in SOC, total N and exchangeable K in the second cropping year were found at greater levels than in the first cropping year possibly due to the root OM input and release of potential available P and K with decline in salinity as indicated by the decreased in pH and salt contents.

3.3. Wheat grain yield

As shown in Table 4, wheat grain yield varied from 0.57 t ha^{-1} in CK0 to 6.61 t ha^{-1} in BPC-PS plot in the first cropping year and from 3.62 t ha^{-1} in CK1 to 4.9 t ha^{-1} and 5.80 t ha^{-1} in BPC-1 and BPC-2 in the second year. As the control plot was somehow recovered of the productivity due to fertilization and tillage as well as root OM input, wheat yield was again increased by 36% in BPC-1 plots and by 60% in BPC-2 plots in the second year of the treatment though the yield was affected by the spring drought in 2012.

The mean wheat grain weight per thousand grains (WPT) ranged from 26.5 g under CK1 to 41.4 g under BPC-2 and grain weight per spike ranged from 1.02 g under CK1 to 1.46 g under BPC-2 in the second year of experiment (Fig. 1b). However, there was no change in total spikes between the treatments.

While number of spikes per hectare and grains per spike was increased by 0.41–10.41% and by 0.42–28.97% respectively under BPC-1 and BPC-2 over CK1 (Fig. 1a and b), a significantly increase was found in thousand grain weight and in grain yield by 23.61% and by 37.48% respectively under BPC-2 over BPC-1 in the second year of experiment. However, as shown in Fig. 1c, there was no visible difference between the BPC-1 and BPC-2 plots in the total shoot biomass production though enhanced under both BPC treatments compared to CK1.

Table 3
Fertility properties of topsoil (0–20 cm) under BPC-PS treatment of the salt stressed soil.

Rotation year	Treatment	SOC (g kg^{-1})	BD (g cm^{-3})	CEC (cmol kg^{-1})	Total N (g kg^{-1})	Available K (g kg^{-1})	Available P (mg kg^{-1})
2010–2011	CK0	5.93 ± 0.21b	1.30 ± 0.05a	25.85 ± 0.55a	0.835 ± 0.02a	0.147 ± 0.004a	24.954 ± 0.591b
	BPC	8.53 ± 1.14a	1.21 ± 0.05b	25.97 ± 3.04a	0.784 ± 0.07b	0.101 ± 0.01b	51.908 ± 1.891a
2011–2012	CK1	6.15 ± 1.83c	1.31 ± 0.02a	23.25 ± 0.61a	0.291 ± 0.02c	0.149 ± 0.003b	25.97 ± 0.82c
	BPC-1	8.52 ± 0.10b	1.23 ± 0.02b	24.84 ± 0.14a	0.791 ± 0.03b	0.116 ± 0.01b	59.75 ± 0.915b
	BPC-2	12.01 ± 0.46a	1.17 ± 0.02c	25.27 ± 0.34a	0.942 ± 0.02a	0.671 ± 0.09a	67.59 ± 0.61a

Different letters in a same column indicate significant differences ($p < 0.05$) between the treatments in a single year.

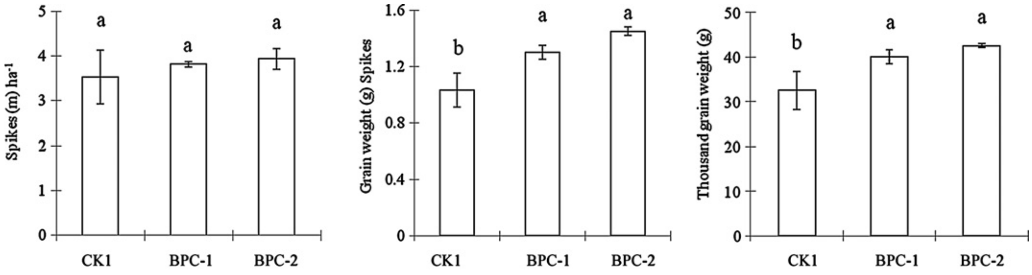

Fig. 1. Spikes million (ha^{-1}) (a), grain weight (g) spikes^{-1} (b) thousand grain weight in gram (c) of wheat under the different treatments. The bar above the block represents the standard deviation of three replicates; Different letters above the blocks indicate significant differences ($p < 0.05$) between the treatments. Symbols and bars represent the mean ± SD ($n = 3$).

4. Discussions

4.1. Mutual effects of BPC-PS on soil salinity

Salt constraint through osmotic and ionic stress threatens crop growth in salt affected croplands (Sperry and Hacke, 2002). Due to the salinity predominated by sodium ion (Na^+), soil became compacted with high BD with deteriorated pore size distribution and soil compaction (Troeh and Thompson, 2005), being unfavorable for salt leaching and root penetrating as well as seed germination. The initial treatment with acid and organic molecular-rich PS could have resulted in enhanced leaching of salts due to high salt solubility and space for downward movement of salts, thus decreasing soil pH value and salt contents. As a porous and OC rich material, biochar has favorable key features to improve soil physical property (Christopher and Atkinson, 2010). The amendment with BPC rice in labile organic carbon from poultry manure could further enhance soil aggregation, increase soil porosity, which could be evidenced by the observed reduction in soil BD. And this could further benefit salt leaching while there is a rain.

Biochar with highly porous structure and large surface area could significantly increase water holding capacity of the sandy soil (Glaser et al., 2002; Cheng et al., 2006; Downie et al., 2009). The application of biochar as the main component of the compost may result in enhanced removal of the soluble salts. In addition, biochar-amended soil could form blocky structure and aggregate, blocking salt upward movement with capillary water. All these may support that amendment with the biochar compost in conjunction with PS created a beneficial condition for salt leaching and reducing salt stress for seed germination and crop growth.

4.2. Effect of BPC-PS on soil nutrient supply and yield

Yield increase in a salt-stressed soil may involve firstly the well germination of seeds and well growth till ripening. Remarkable reduction in crop grain yield under salt stress in croplands has been widely reported (Li et al., 2000; Zhu, 2001; Xu et al., 2002; Harris et al., 2010; Joseph and Jini, 2011). Either positive (Shirakawa et al., 1993; Blackwell et al., 2007; Asai et al., 2009; Major et al., 2010; Zhang et al., 2011) or insignificant (Cui et al., 2011; Liu et al., 2012) and even negative (Kishimoto and Sugiura, 1985) effects of biochar amendment in large amounts on crop yield have been reported. Here, wheat yield was observed increased significantly under BPC-PS amendment as compared to the unamended soil. This could be attributed to multiple effects by the combined application of the BPC compost and the PS solution to the salt affected soil.

Salt stress can influence the germination rate and survival rate of the crops. Germination of seeds and the seedling plant growth could be greatly limited by the osmotic pressure, access to moisture and oxygen, toxification by replaceable sodium (Wilson et al., 2002; Bybordi and Tabatabaei, 2009). Seed germination has been generally favored with reduction in soil salinity though it was not shown in this study. Application of pyroligneous solution could promote germination and radicle growth at an appropriate dilution (Mu et al., 2003, 2004). Shirakawa et al. (1993) reported that application of charcoal in conjunctions of pyroligneous acid improved the physiological activities of rice crop. Rice growth improvement under pyroligneous acid was observed by Ichikawa and Ota (1982) though this effect may be not always prominent for other crops (Souza et al., 2006). Nevertheless, in a work by Pangnakorn et al. (2009), application of wood vinegar and fermented liquid organic fertilizer did not induce significant difference in yield and the yield components among treatments.

In the present experiment, BPC-PS amendment increased soil phosphorus availability which has been recognized as a limiting factoring in alkaline salt soils (Abrol et al., 1988; Grattan and Grieve, 1999; Elgharably, 2008). Here, available phosphorus as measured by Olsen method was seen increased under BPC-PS treatment by over 100% compared to the unamended soil. Olsen-P content under BPC-PS was increased to over 50 mg kg^{-1}, a level generally accepted

Table 4
Wheat grain yield under treatments of the salt stressed soil.

Rotation year	Treatment	Grain yield (t ha^{-1})
2010–2011	CK0	0.57 ± 0.01b
	BPC	6.61 ± 1.25a
2011–2012	CK1	3.62 ± 0.57b
	BPC-1	4.94 ± 0.19a
	BPC-2	5.80 ± 0.55a

Different letters in a same column indicate significant differences ($p < 0.05$) between the treatments in a single year.

as favorable for crop growth (Gupta et al., 1990). This could be explained by the high content of available P in the BPC (Table 3) and also by the decreased soil pH by 0.3 under BPC-PS compared to the unreclaimed soil (Table 2). In this experiment, biomass production, total spikes per hectare was not different between the treatments in the second cropping year but the yield different was found coincident with the difference in grain weight per spike and in weight per thousand grains (Fig. 1b and c). This suggested that grain filling under BPC-PS treatment was better than without treatment, which could be attributed to the increase in total N and available P and K in the amended soils.

Furthermore, biochar effect on increasing crop yield may act through improving soil physical and chemical conditions (Chan et al., 2007, 2008), which could benefit N and P translocation from shoot to grain, leading to an increase in yield under BPC-PS treatment. Improved P and N availability under biochar amendment had been well addressed in the work by Lehmann et al. (2003) and Glaser et al. (2002) in the rice, cowpea and oats.

Therefore, the salt stressed soil was reclaimed by BPS-PC treatment through biochar effects on improving soil structure for root growth and on preserving N, and through PS effect on leaching soluble salt and enhancing availability of P and K in conjunction with labile nutrient supply from the poultry manure compost. These effects offer an overall unique beneficial condition for wheat growth in the salt stressed soil. Consequently, high grain yield was reached even in a year of drought.

5. Conclusions

Combined amendment of BPC and PS significantly improved both the physical and chemical conditions of the salt-stressed soil and thus increasing wheat production through a decline in soil salinity. This could be accounted for by the multiple benefits on salt leaching, improvement of soil fertility, nutrient supply and translocation to the grain under the amendment. This experiment suggested a great potential to use a combined amendment of poultry manure compost with biochar and the pyroligneous solution from crop straw pyrolysis for alleviating salt stress in croplands. However, the mechanism behind deserves further research.

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