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ORIGINAL ARTICLE

Characterization of biochars produced from seven biomasses grown in three different climate zones

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Abstract The characterization of biochars produced from seven feedstocks (four crop straws: cotton stalks, wheat stalks, rape stalks and corn stalks; three hardwoods: Salix babylonica Linn, Platanus orientalis and Robinia pseudoacacia) grown in three different climate zones (arid, semiarid and humid regions) were investigated for their potential as soil amendments. The results show that ash content, K^+, Ca^{2+}, Mg^{2+}, CEC, Cl^-, pH, and salinity are generally higher in the straw biochars (STR-BCs) than the hardwood biochars (HW-BCs). However, there is no significant distinction between the two categories of biochars in terms of surface acidity, surface basicity, TC, available phosphorus (A-P) or NH_4^+-N. The contents of K^+, Na^+, Ca^{2+}, Mg^{2+}, EC, Cl^- of all 21 biochars increase in semiarid and arid regions in comparison to humid regions, while ash content, TC, CEC, pH, surface acidity, surface basicity, A-P and NH_4^+-N show no correlation to the climate. From the perspective of K^+, CEC and the remediation of acidified soils, STR-BCs are preferable over HW-BCs as a soil amendment, while HW-BCs are more suitable than STR-BCs in soils with a saline problem. EC, Na^+ and Cl^- increase with the water stress of the climatic regions, and the high saline ions of biochar in the arid regions indicate that biochars produced from local biomass, especially from crop residues, are at a high risk of exacerbating soil salinization. The big difference in the critical chemical properties, such as the saline ions, stresses that biochar should be taken on a regional basis as well as a biomass basis, with the general assumption that whether biochar as a soil amendment is good or bad is groundless.

Keywords Biochar · Crop straw · Hardwood · Characterization · Soil amendment

1 Introduction

As a soil amendment, biochar has attracted much attention in recent years due to its importance in carbon-sequestration and soil improvement (Wang et al. 2011; Nelissen et al. 2012; Ameloot et al. 2013; Biederman and Harpole 2013). Many studies have shown that the application of biochar in soil reduces N_2O emissions (Knoblauch et al. 2011; Mukome et al. 2013; Wang et al. 2011; Zhang et al. 2014), while increasing crop yield (Major et al. 2010; Prendergast-Miller et al. 2011; Nelissen et al. 2012; Wang et al. 2012; Zhang et al. 2012) by improving soil water holding capacity, nutrients retention capacity, soil biota and pH (Lehmann et al. 2006, 2011; Blackwell et al. 2010; Chen et al. 2010; Laird et al. 2010). Some other studies, however, did not observe this positive effect (Deenik et al. 2010; Gaskin et al. 2010; Van Zwieten et al. 2010). These contradicting findings may have resulted partly from the variations in biochar quality. Previous studies have indicated that the physicochemical properties of biochars not only depend on the pyrolysis conditions, but also on the type of feedstocks (Chan et al. 2007; Gaskin et al. 2008; Chan and Xu 2009; Singh et al. 2010; Enders et al. 2012). In a recent study on five feedstocks, for example, it was

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found that wood biochar had higher total C, lower ash content, lower total N, P, K, S, Ca, Mg, Al, Na and Cu content, and a lower potential cation exchange capacity (CEC) and exchangeable cations than the manure-based biochars. Meanwhile, the papermill sludge biochar had the highest total and exchangeable Ca, $CaCO_3$ equivalence, total Cu and potential CEC and the lowest total and exchangeable K (Singh et al. 2010). Although a lot of studies have been conducted to investigate the effect of pyrolysis conditions and feedstocks types on biochar, it is not clear whether climatic conditions can affect the qualities of biochars produced from the same feedstock species.

In our most recent field experiment in the arid region of western China, we found that biochars produced from the local biomass invariably had much higher Na^+ and Cl^- than their counterparts in the subtropical western China. These ions are critical for determining the salinization of the soil. They are so high in the biochar made from the biomass of the arid region that the rate of cottonseeds sprouting was significantly reduced. These findings indicate that biochars produced from the same feedstock species in different climatic zones may have much larger differences in their physicochemical properties than was previously understood. Understanding the difference is critical in biochar application in agriculture, as well as in the evaluation of newly emerged technology, and thus merits detailed examinations. However, few studies have been reported on this issue (Singh et al. 2010; Carrier et al. 2012; Uras et al. 2012), and even less have been reported on the variation of the saline ions from different climatic zones. Therefore, we studied the difference by analyzing the biochars produced from the same feedstock species but grown in different climate zones.

2 Materials and methods

2.1 Biomass and biochar production

Four species of crop straws (STR) and three species of hardwoods (HW) were collected from each of the three climate zones. The STR included cotton stalk (C), wheat stalk (W), rapeseed stalk (R) and corn stover (S). The HW included Salix babylonica Linn (SB), Platanus orientalis (PO) and Robinia pseudoacacia (RP). The three climatic zones were the arid region (A, annual precipitation, <100 mm), semi-arid region (SA, annual precipitation, 400–600 mm) and humid region (H, annual precipitation, >1000 mm), respectively. The biomass in the arid climatic region was collected in Kashgar, Xinjiang Uygar Autonomous Region, west China, and the feedstocks in the semi-arid region were obtained from three areas: C, W and PO in Shijiazhuang City, Hebei Province, north China, R in Lanzhou City, Gansu Province and S, SB, RP from Baotou City, Inner Mongolia, north China. The raw material in the humid zone was collected in Guiyang City, Guizhou Province, west China. The crop straws were grown in farmland tilled and managed in the conventional way of Chinese farmers. The hardwood trees were grown in non-fertilized forests, which were about 10-year old. The crop straws were sampled in 3 patches from the field and the hardwood in 4 trees. The sample straw totaled to about 5 kg in weight and the hardwood totaled to about 10 kg.

All the samples were sectioned into pieces less than 2 cm in length and 5 mm in diameter and then dried at 105 °C for 24 h before pyrolysis. The prepared sample was pyrolyzed in a stainless steel rectangular box (5.07 L) installed in a muffle furnace (Tianjin Taisite Instrument Co., ltd, SX-12-10). The heating rate, final temperature and holding time was 18 °C·min^{-1}, 550 °C and 30 min, respectively.

2.2 Physicochemical analyses

The biochars were homogenised and sieved to a particle size of less than 0.15 mm (100 mesh) for all analyses. All the analyses were performed in duplicate, except those of total elements and water-soluble anion concentrations. Unless noted otherwise, the chemical reagents were guaranteed reagents (GR, Tianjin Kermel Ltd.).

2.2.1 Moisture and ash contents

An aliquot of 2 g of the samples were air-dried for 24 h at 105 °C, weighed and then transferred to a muffle furnace. The temperature was set to 750 moisture and the ash contents were determined by the loss of weight in the heating (ASTM D1762-84).

2.2.2 Total elemental contents

The total C, N, H and S contents were determined by dry combustion analysis using an Elementar (vario MACRO CNS; Elementar, Germany). Total O was calculated using the ASTM method as follows (Enders et al. 2012):

To determine the major cations (K^+, Na^+, Ca^{2+} and Mg^{2+}) in the feedstocks, an aliquot of about 500 mg of the samples was weighed and then treated by the nitric-perchloric acid wet digestion method (Miller and Kalra 1998). After the digestion was complete, the solution was introduced to an ICP-OES (ICP, Varian Vista Pro, Varian Inc., Palo Alto, CA, USA) to measure the cations.

2.2.3 PH of biochar

An aliquot of 1.25 g of biochar was added to 25 mL of distilled water in a glass beaker, and then shaken for

30 min. After the solution was left still for 10 min, the supernatant was used for measuring the pH using a pH Meter (PHS-3CT, Shanghai WeiYe instrument) (Cheng and Lehmann 2009).

2.2.4 Cation exchange capacity (CEC)

The CEC of the biochars was determined using the method recommended by Page (1982). 0.5 g of the ground biochar was introduced to a 50 mL centrifuge tube and shaken with 10 mL of saturating solution (0.4 N NaOAc—0.1 N NaCl, 60 % ethanol solution adjusted to pH 7.0 using 3 M HCl). Then the tubes were centrifuged at 4200 rpm (XiangYi Centrifuge L530). After the biochar was deposited in the bottom of the tube, the supernatant was decanted. This procedure was repeated three times to ensure the complete saturation of the cation exchange sites with Na^+.

The treated biochar was added to 10 mL of extracting solution 0.25 M $Mg(NO_3)_2$ and shaken for an hour to exchange the Na^+ with the Mg^{2+}. The suspension was centrifuged and the supernatant was decanted into a 50 mL volumetric flask. This procedure was repeated three times to ensure all Na^+ was exchanged and extracted. The collected supernatants were made up to 50 mL with distilled water. The concentrations of Na^+ and Cl^- in the solution were determined by ion chromatography (DIONEX ICS-90). The CEC ($cmol_c\ kg^{-1}$) was calculated by the total amount of exchangeable Na^+ (Carrier et al. 2012).

2.2.5 Boehm titration

The total surface acidity and alkalinity of the biochar was determined by Boehm titration and based on its method (Boehm 1994). 0.15 g biochar was added to 15 mL of either 0.1 N NaOH or 0.1 N HCl solution and shaken with an end-over-end shaker for 40 h. The slurry was then filtered through the ShuangQuan medium speed filter. An aliquot of 5 mL of the NaOH filtrate was transferred to a 10 mL 0.1 N HCl solution, which neutralized the unreacted base. The solution was back titrated with 0.1 N NaOH in the presence of a phenolphthalein indicator. Surface basicity was measured similarly to the measurement of surface acidity; an aliquot of 5 mL of the HCl filtrate was back titrated with 0.1 N NaOH. The base or acid uptake of the biochar was converted to surface acidity or surface basicity ($mmol{\cdot}g^{-1}$), respectively.

2.2.6 Electrical conductivity (EC) and water soluble nutrients

For the determination of water-soluble nutrients (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and NO_3^-), 1.5 g biochar was shaken with 30 mL distilled water for 1 h and the suspension was then filtered through the ShuangQuan medium speed filter. The EC was measured with a HANNA HI9033 conductivity meter and the cation and anion concentrations were determined using the ICP-OES (ICP, Varian Vista Pro, Varian Inc., Palo Alto, CA, USA) and ion chromatography (DIONEX ICS-90), respectively.

2.2.7 NH_4^+-N and A-P

NH_4^+-N of biochar was extracted by shaking 1 g biochar with 40 mL 2.0 N KCl for 1 h and the suspension was then filtered through the ShuangQuan medium speed filter. The NH_4^+-N concentration in the filtrate was determined by the indophenol blue colorimetric method. A-P was extracted by shaking 1 g biochar with 40 mL 0.5 N $NaHCO_3$ (pH 8.5) for 30 min and the suspension was then filtered through the ShuangQuan medium speed filter. The P concentration in the filtrate was determined by the ascorbic acid method (GB 12297-90).

2.3 Statistical analyses

Statistics were performed using SPSS 16.0 software. The mean separation and correlation analysis of ash, TC, CEC, water soluble ions, pH and surface acidity and basicity were conducted based on 2-way ANOVA (feedstock type × climate condition) using the LSD (least significant difference) at the significance level $P = 0.05$. All figures were drawn using Origin 8.0 software.

3 Results and discussion

3.1 Ash content, elemental contents and cation exchange capacity (CEC)

The ash and TC content of 21 biochars ranged about 3.6–33.1 % and 53.0–80.1 %, respectively (Table 1). The ash and TC contents varied significantly between STR-BCs and HW-BCs ($P < 0.05$), though they did not vary between the biochars in the three climatic zones (A, SA and H). This indicated that the ash and TC contents of the biochars were mainly affected by the feedstock types but little affected by the environment.

The C: N molar ratio of the biochars varied considerably from 34.8 to 215.8. There was no significant difference between the STR-BCs and HW-BC, as well as biochars in the three climatic zones. The high C: N concurred to the suggestion that the addition of biochar to the soil would cause soil N immobilization and possibly induce N deficiency in plants when applied to the soils alone (Stevenson 1994; Chan and Xu 2009). Normally, a C: N of 20 induces no influences between C and N (Leeper and Uren 1993). This criterion, however, is not necessarily true for biochar

Table 1 The ash content and elemental analyses of 21 biochars

Biochar	Ash (wt%)			Total C (wt%)			Total N (wt%)			Total H (wt%)			Total S (wt%)			Total O (wt%)		
	Arid	Semiarid	Humid	Arid	Semiarid	Humid	Arid	Semiarid	Humid	Arid	Semiarid	Humid	Arid	Semiarid	Humid	Arid	Semiarid	Humid
C	19.1	8.8	10.1	64.3	71.9	69.3	1.5	1.9	1.5	3.4	4.8	3.5	0.7	0.3	0.1	11.0	12.3	15.5
W	21.5	25.4	33.1	58.8	58.7	53.0	0.9	1.2	1.1	4.2	5.0	4.8	0.5	0.4	0.4	14.2	9.3	7.6
R	10.1	19.5	13.8	70.1	64.1	68.8	0.6	2.0	1.9	4.1	4.9	7.0	0.4	0.8	0.5	14.7	8.8	7.9
S	23.6	11.6	13.9	68.1	68.6	72.4	2.3	2.0	0.5	3.6	5.8	3.1	0.3	0.2	0.2	2.2	11.7	10.0
RP	4.6	7.7	7.1	76.1	71.5	80.1	2.0	1.5	1.6	4.4	2.8	4.2	0.2	0.1	0.2	12.7	16.4	6.9
PO	13.2	3.6	4.0	67.7	79.7	71.9	1.5	1.0	0.6	3.7	5.8	4.1	0.4	0.2	0.1	13.6	9.7	19.3
SB	10.0	9.2	6.4	72.3	66.0	77.2	1.7	0.4	0.7	4.0	2.2	4.9	0.2	0.1	0.2	11.7	22.1	10.7

C cotton stalk, *W* wheat stalk, *R* rape stalks, *S* corn stalk, *SB* Salix babylonica Linn, *PO* Platanus orientalis, *RP* Robinia pseudoacacia; *Arid* arid region, *Semiarid* semiarid region, *Humid* humid region

because much of its C is chemically and biologically inert and thus difficult to mineralize (Forbes et al. 2006). This suggests that biochar application may not necessarily lead to significant N immobilization, as soils do with similar C: N (Carrier et al. 2012). However, there are studies proving that biochar addition causes lower N uptake in plants (Rondon et al. 2007; Asai et al. 2009; Santalla et al. 2011). This probably resulted from the small portion of easily-mineralizable C in freshly-produced biochar, the bulk of the remaining organic C (with even higher C/N) do not cause N immobilization (Chan and Xu 2009).

CEC is an important indicator of the potential of biochar to reversibly adsorb cations as a soil amendment to enhance fertility (Brewer et al. 2011). The negatively charged functional groups (e.g. carboxyl and phenolic groups) on the charcoal surface retain and attract cations in soil water and consequently, the application of biochar with high CEC enhances the nutrient holding capacity of soil, reducing the nutrient loss from leaching (Page 1982; Uras et al. 2012). The CEC of 21 biochars ranged from 90.01 to 314.33 $cmol_c \cdot kg^{-1}$ and averaged at 174.77 $cmol_c \cdot kg^{-1}$ (Fig. 1). There were no significant differences among the biochars in the three climatic zones (A, SA and H). However, the STR-BCs differed significantly to HW-BCs ($P < 0.01$) with a mean value 222.32 and 111.36 $cmol_c \cdot kg^{-1}$, respectively. CEC ranged from about 125.45–314.33 $cmol_c \cdot kg^{-1}$ for the four STR-BCs, similar to the results of other studies, which reported it as 210–304 $cmol_c \cdot kg^{-1}$ for straws of canola, corn stover, soybean and peanut that were pyrolyzed at 500 °C (Xu et al. 2011). CEC ranged from 90.01 to 144.05 $cmol_c \cdot kg^{-1}$ for the three HW-BCs, which was much lower than the STR-BCs. The results of the CEC indicated that the CEC of biochar were mainly controlled by the feedstock but little by the environment.

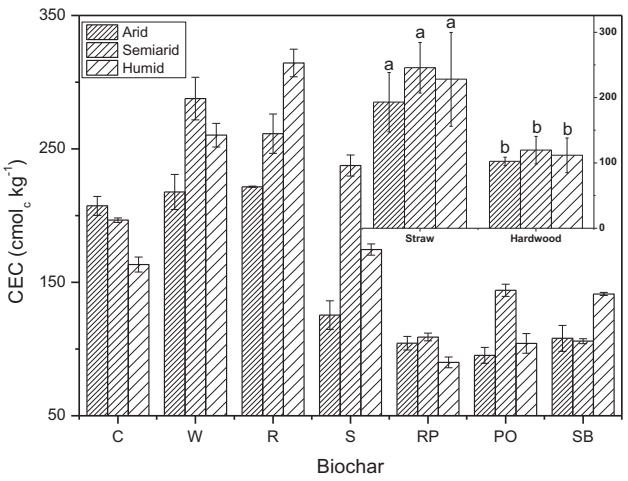

Fig. 1 The CEC values of the 21 biochars. Means in columns followed by the same letter were not significantly different at $P < 0.05$ using the LSD test

3.2 Nutrient contents (NH_4^+-N and A-P, K^+, Ca^{2+}, Mg^{2+})

Water-soluble nutrients in biochar are the ones directly available to plants. N, P, K, Ca, Mg and S, in particular the former three, are regarded as the universally essential plant macronutrients (Havlin et al. 2005). Since plant growth utilizes the nutrients in their inorganic forms, such as NO_3^- and NH_4^+ for N (Chan et al. 2008), we only reported the inorganic ones here. The contents, average and mean values of NH_4^+-N and A-P, K^+, Ca^{2+}, Mg^{2+} are shown in Fig. 2 and Table 2.

NH_4^+-N concentrations of the 21 biochars were very low (3.46–6.43 $mg \cdot g^{-1}$) and had no significant differences between the STR-BCs and HW-BCs and among the three climate zones. NO_3^--N was so low that it was below the detection limit in all 21 biochars. The low concentration of the inorganic N corroborated the previous report that N in biochars was primarily in the form of condensed, heterocyclic structures (Koutcheiko et al. 2007), which was mostly recalcitrant and plant-unavailable (Brewer et al. 2009). The content of plant-available phosphorus (A-P) had no significant difference between the STR-BCs and HW-BCs, as well as biochars in the three climate regions. These values, however, were significantly higher than the wood biochar (<5 $mg \cdot kg^{-1}$) and eucalyptus leaf biochars (60–120 $mg \cdot kg^{-1}$) reported by Singh and his coworkers (Singh et al. 2010). The content of K^+ in STR-BCs was significantly higher than the HW-BCs ($P < 0.05$) and the

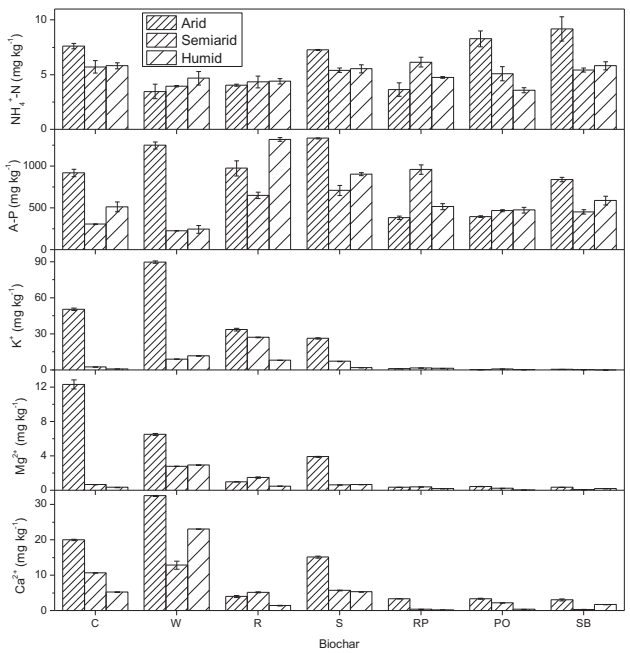

Fig. 2 Nutrient contents (NH_4^+-N, A-P, K^+, Mg^{2+} and Ca^{2+}) of the 21 biochars

Table 2 The range and mean values of nutrient contents (NH_4^+-N, A-P, K^+, Mg^{2+} and Ca^{2+}) of STR and HW

Biochar	NH_4^+-N ($mg \cdot kg^{-1}$)		A-P ($mg \cdot kg^{-1}$)		K^+ ($mg \cdot g^{-1}$)		Mg^{2+} ($mg \cdot g^{-1}$)		Ca^{2+} ($mg \cdot g^{-1}$)	
	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average
Straw	3.5–7.6	5.2 ± 1.3	226.2–1333.4	779.3 ± 404.7	0.9–89.8	22.4 ± 26.1 A	0.3–12.3	2.8 ± 3.5 A	1.4–32.5	11.8 ± 9.4 A
Hardwood	3.6–9.2	5.8 ± 1.9	383.7–960.3	564.8 ± 202.0	0.1–1.7	0.7 ± 0.6 B	0.1–0.4	0.3 ± 0.1 B	0.2–3.4	1.7 ± 1.4 B

Means in columns followed by the same letter were not significantly different at $P < 0.05$ using the LSD (least significant difference) test

K^+ concentration in the arid region was significant higher than in the humid region ($P < 0.05$). K^+ content of HW-BCs was lower than the black wattle biochar (2.3 $mg \cdot g^{-1}$) and vineyard biochar (4.38 $mg \cdot g^{-1}$) (Uras et al. 2012), but a little higher than the sugar cane bagasse biochar (0.56 $mg \cdot g^{-1}$) (Carrier et al. 2012). Again, Ca^{2+} in the STR-BCs was significantly higher than HW-BCs ($P < 0.01$) and no significant difference was found between the biochars in the three climate zones. The STR-BCs were also much higher than the ones in literature (Carrier et al. 2012; Uras et al. 2012). However, the Ca^{2+} content of the HW-BCs was even lower than that of the wood biochars (1.11–5.54 $mg \cdot g^{-1}$) reported in literature (Singh et al. 2010). The high Ca^{2+} content could limit the availability of Mg^{2+} if added to soil (Carrier et al. 2012; Uras et al. 2012). Similar to Ca^{2+}, the Mg^{2+} in the STR-BCs was significantly higher than the HW-BCs ($P < 0.05$) and no significant difference was found between the biochars in the three climate zones. The Mg^{2+} of HW-BCs was also lower than that of the wood biochars (0.03–0.048 $mg \cdot g^{-1}$) and eucalyptus leaf biochars (0.49–0.61 $mg \cdot g^{-1}$) (Singh et al. 2010).

The NH_4^+-N contents had no significant difference among the three climate regions in either STR-BCs or HW-BCs (Table 3; biochars were classified into 6 types: 2 types of biochar × 3 climatic zones). The A-P of STR-BCs in the arid and humid climate zones was significantly higher than in the semiarid climate ($P < 0.05$). This, however, was not the case for the HW-BCs, which showed no significant differences among the three climate regions. No significant correlation was observed between climate and the content of the plant available nutrients, suggesting that the climate was not a factor in the content of NH_4^+-N and A-P in the biochars. The content of K^+ in STR-BCs increased systematically from the humid climate to semi-arid and arid climate regions. Apparently, this was a result of the K^+ difference of the straw in the different climatic regions (Fig. 3). The K^+ in the HW-BCs did not vary systematically in the three climatic zones, in either the charcoal or the biomasses. Similarly, there were no significant differences in the Ca^{2+} in the three climate regions for either the STR-BCs or HW-BCs. Like K^+, Mg^{2+} in the STR-BCs increased systematically from the humid region to the semi-arid and arid regions, while no differences of HW-BCs were observed in the three climate regions (Table 3).

3.3 PH, surface acidity, surface basicity and salinity (EC, Na^+, Cl^- and SO_4^{2-})

The pH of the biochars ranged from 9.27 to 10.53 with a mean value 9.75 for the STR-BCs and 7.98 to 10.57, with a mean value of 9.02 for the HW-BCs (Table 4). No significant difference was observed either between STR-BCs and HW-BCs or among the three climate zones. This indicated that regardless of the climate, the pH of biochar from all the biomass were alkaline in chemical property, which was consistent with the other studies (Lehmann et al. 2010; Xu et al. 2011), and that the biochar provided a potential way to remediate soils that were acidified by the over-dosing of chemical fertilizers.

The mean surface acidity and basicity of the 21 biochars averaged 2.01 $mmol \cdot g^{-1}$, ranging from 0.82 to 3.23 $mmol \cdot g^{-1}$, and 0.98 $mmol \cdot g^{-1}$ with a range about 0.10–3.26 $mmol \cdot g^{-1}$, respectively (Table 4). There was no significant differences between the climatic regions or between the STR-BCs and HW-BCs. Surface acidity reflects the number of acid functional groups (e.g. carboxyls and phenols) on the surface of biochar. The mean surface acidity of the STR-BCs (2.20 $mmol \cdot g^{-1}$) was slightly higher than that of the HW-BCs (1.76 $mmol \cdot g^{-1}$),

Table 3 The mean nutrient contents (NH_4^+-N, A-P, K^+, Mg^{2+} and Ca^{2+}) of STR-BCs (STR) and HW-BCs (HW) in 3 regions

Biochar group	NH_4^+-N ($mg \cdot kg^{-1}$)	A-P ($mg \cdot kg^{-1}$)	K^+ ($mg \cdot g^{-1}$)	Mg^{2+} ($mg \cdot g^{-1}$)	Ca^{2+} ($mg \cdot g^{-1}$)
Arid					
Straw	5.6 ± 2.2 A	1119.1 ± 203.0 A	50.1 ± 28.3 A	5.9 ± 4.8 A	17.9 ± 11.8 A
Hardwood	7.0 ± 3.0 A	540.2 ± 260.1 B	0.6 ± 0.5 B	0.4 ± 0.1 B	3.3 ± 0.18 B
Semiarid					
Straw	4.9 ± 0.9 A	473.1 ± 242.1 B	11.5 ± 10.9 B	1.4 ± 1.0 B	8.6 ± 3.8 AB
Hardwood	5.6 ± 0.6 A	627.2 ± 288.6 B	1.0 ± 0.7 B	0.2 ± 0.2 B	1.0 ± 1.1 B
Humid					
Straw	5.1 ± 0.7 A	745.9 ± 469.3 A	5.7 ± 5.1 B	1.1 ± 1.2 B	8.8 ± 9.7 AB
Hardwood	4.7 ± 1.1 A	526.9 ± 58.0 B	0.5 ± 0.7 B	0.2 ± 0.1 B	0.8 ± 0.8 B

Means in columns followed by the same letter were not significantly different at $P < 0.05$ using the LSD test

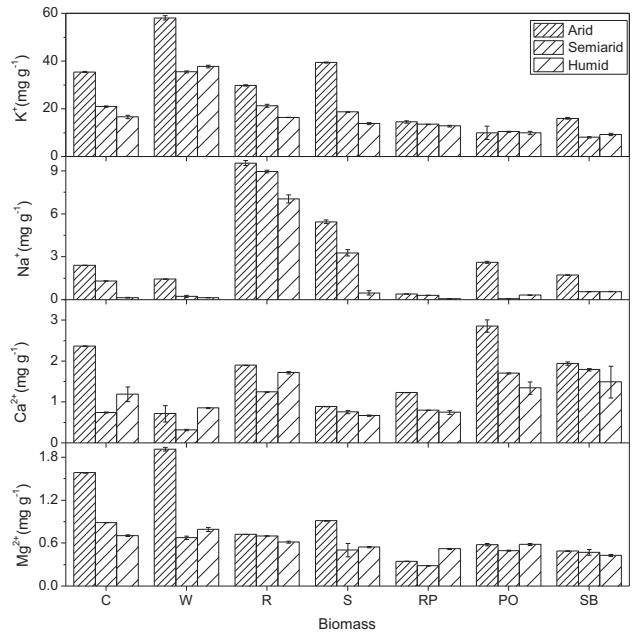

Fig. 3 The total K^+, Na^+, Ca^{2+} and Mg^{2+} concentration of the 21 biomasses

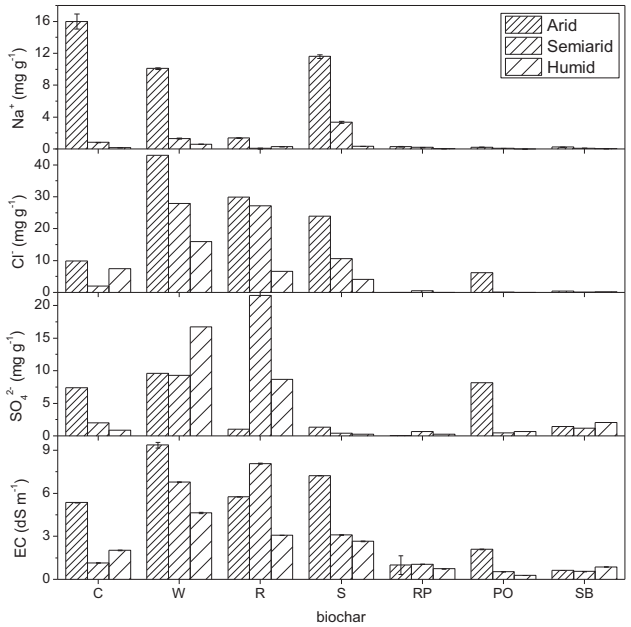

Fig. 4 The EC and salinity ions (Cl^-, SO_4^{2-} and Na^+) concentration of the 21 biochars

which was quite consistent with the CEC results ($P < 0.05$).

The EC of the biochars ranged from 1.15 to 9.36 ds·m^{-1} (mean value 4.94 ds·m^{-1}) in the STR-BCs and 0.28–2.10 (mean value, 0.86 ds·m^{-1}) in the HW-BCs. The former was significantly higher than the latter ($P < 0.01$) and no significant difference was found between the biochars in the three climate regions. Nevertheless, the EC of the STR-BCs decreased in order from the arid region (6.92 ds·m^{-1}) to the semi-arid region (4.78 ds·m^{-1}) and then the humid region (3.10 ds·m^{-1}); the same trend was also observed for the HW-BCs (Fig. 4, Table 5). The STR-BCs was significantly higher than the HW-BCs in this property ($P < 0.01$). The EC is a measure of the total water soluble ions (salinity) present in the biochar, and the high EC impairs crop growth by decreasing plant water uptake, while affecting the nutrient balance (Chan et al. 2008). This harmful nature seems to increase with the water stress of the climate. An EC higher than 4.0 ds·m^{-1} is a threshold demarcating the saline soil in soil water extract experiments (Carrier et al. 2012). In all 21 biochars, 7 biochars, including all STR-BCs in the arid region (C, W, R and S), two STR-BCs in the semiarid regions (W and R) and one STR-BC (W) in the humid region were higher than 4.0 ds·m^{-1} in EC (Fig. 4), and were thus categorized as saline in the chemical property. The application of biochars made of the local biomass may have exacerbated the soil salinization in the arid regions.

Na^+, Cl^- and SO_4^{2-} are the major harmful ions in salinized soils, and thus pose major concerns to biochars in arid regions. Na^+ ranged from 0.06 to 16.00 mg·g^{-1} (mean value, 3.84 mg·g^{-1}) in STR-BCs and 0.02–0.30 (mean value, 0.14 mg·g^{-1}) in HW-BCs. It was significantly higher in STR-BCs than in HW-RCs ($P < 0.01$) and increased systematically in both categories of biochars from the humid to semi-arid and arid climatic regions (Table 5). Cl^- ranged

Table 4 The pH, surface acidity and surface basicity of the 21 biochars

Biochar	PH (1:20 water, w/v)			Surface acidity (mmol·g^{-1})			Surface basicity (mmol·g^{-1})		
	Arid	Semiarid	Humid	Arid	Semiarid	Humid	Arid	Semiarid	Humid
C	10.3	9.6	9.8	2.8	2.0	2.2	3.3	0.6	1.2
W	9.4	9.5	9.3	2.8	3.2	2.4	0.4	1.1	0.2
R	9.5	9.7	9.6	2.6	2.5	1.6	1.0	2.1	1.6
S	10.2	9.8	10.5	0.8	2.5	1.0	0.7	1.4	1.0
RP	8.5	9.8	10.6	2.0	1.3	1.0	0.45	1.0	0.3
PO	9.0	8.9	8.0	1.8	1.8	1.5	0.8	0.2	0.1
SB	9.6	8.0	9.0	1.9	2.7	1.8	1.3	1.0	0.8

Table 5 The mean EC and salinity ions (Cl^-, SO_4^{2-} and Na^+) concentration of STR-BCs and HW-BCs in three regions

Biochar group	EC ($ds \cdot m^{-1}$)	Cl^- ($mg \cdot g^{-1}$)	SO_4^{2-} ($mg \cdot g^{-1}$)	Na^+ ($mg \cdot g^{-1}$)
Arid				
Straw	6.9 ± 1.8 A	26.7 ± 13.7 A	4.8 ± 4.3 A	9.8 ± 6.1 A
Hardwood	1.2 ± 0.8 B	2.2 ± 3.4 B	3.2 ± 4.3 A	0.3 ± 0.0 B
Semiarid				
Straw	4.8 ± 3.2 AC	16.9 ± 12.8 AC	8.3 ± 9.6 A	1.4 ± 1.4 B
Hardwood	0.7 ± 0.3 B	0.3 ± 0.2 B	0.8 ± 0.4 A	0.1 ± 0.1 B
Humid				
Straw	3.1 ± 1.1 BC	8.5 ± 5.1 BC	6.6 ± 7.7 A	0.4 ± 0.2 B
Hardwood	0.6 ± 0.3 B	0.1 ± 0.1 B	1.0 ± 0.9 A	0.0 ± 0.0 B

Means in columns followed by the same letter were not significantly different at $P < 0.05$ using the LSD test

from 1.95 to 42.97 $mg \cdot g^{-1}$ (mean value, 17.36 $mg \cdot g^{-1}$) in STR-BCs and 0.03–6.16 (mean value, 0.86 $mg \cdot g^{-1}$) in HW-BCs. STR-BCs was significant higher than HW-RCs ($P < 0.01$). Cl^- also increased with the stress of water as Na^+ did. Unlike Na^+ and Cl^-, SO_4^{2-} content showed no trend with the climate zones but was higher in the STR-BCs (mean value, 6.59 $mg \cdot g^{-1}$) than the HW-RCs (mean value, 1.65 $mg \cdot g^{-1}$), though the differences were not significant. This was probably caused by the application of a SO_4^{2-} based chemical fertilizer such as ammonium sulfate. Salinization is the primary problem for the agriculture in arid regions; Na^+ and Cl^-, SO_4^{2-}, especially the former two ions, usually exceed the tolerance of the crops grown. Farmers have to use flooding methods to leach out the ions during the fallow season, which consumes large amounts water, a precious resource in the arid region. The high content of the salinity ions in the biochars corroborates with EC that the application of biochars in arid regions would put the crops at higher risk of salinization.

4 Conclusions

Based on the current data, we found that ash content, K^+, Ca^{2+}, Mg^{2+}, CEC, Cl^-, PH, and salinity are generally higher in the STR-BCs than in the HW-BCs. This is, however, eas not the case with surface acidity, surface basicity, TC, A-P and NH_4^+-N, which showed no significant distinction between the two categories of biochars. The K^+, Na^+, Ca^{2+}, Mg^{2+}, EC, Cl^- in all the 21 biochars increased in semi-arid and arid regions, in comparison to humid regions, while ash content, TC, CEC, PH, surface acidity, surface basicity, A-P and NH_4^+-N showed no correlation to the climate. From the perspective of K^+, CEC and the remediation of acidified soils, STR-BCs are preferable over HW-BCs as a soil amendment, while HW-BCs are more suitable than STR-BCs are for saline soils. EC, Na^+ and Cl^- increase with the water stress of climatic regions, and the high saline ions of biochar in the arid regions indicate that biochars produced from the local biomass, especially from the crop residues, have a high risk of exacerbating soil salinization. The solution to this problem of biochar as a soil amendment in the arid regions has yet to be studied. The big difference in the critical chemical properties, such as the saline ions, stresses that biochar should be taken on regional basis and also on biomass basis, with the general assumption that whether biochar as a soil amendment is good or bad is groundless.

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