ORIGINAL RESEARCH

Comparison of biochar properties from 5 kinds of halophyte produced by slow pyrolysis at 500 °C

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Received: 29 June 2021 / Accepted: 23 January 2022
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Abstract

Glycophyte biomass-derived biochars are currently concerned in most studies. However, little attention is given to the characteristics of halophyte-derived biochars. In this study, five typical halophytes of euhalophytes (*Suaeda altissima*, *Suaeda salsa*, and *Kalidium foliatum*), recrotohalophytes (*Phragmites australis*), and pseudohalophytes (*Tamarix chinensis*) which are widely distributed in the arid and semiarid regions of northwestern China were selected for producing biochars with a slow pyrolysis process at 500 °C for 1 h. The harvested biochars were characterized in elemental content, pores, surface area, and surface charges, and then their potential value as a soil conditioner was evaluated. The results showed that the halophyte-derived biochars had variable ash and Na⁺ contents, ranging from 7.26 to 23.64% and 1.06 to 33.93 g kg⁻¹ respectively. The EC value of the biochars ranged from 1.76 to 23.45 mS cm⁻¹. The biochar derived from *Suaeda altissima* had a very low specific surface area (SSA), 3.50 m² g⁻¹, while that derived from *Phragmites australis* (B_{PA}) had a very high SSA, 344.02 m² g⁻¹. All the biochars carried both positive and negative charges. *Kalidium foliatum* biochar (B_{KF}) possessed more negative charges, while *Suaeda altissima* biochar (B_{SA}) contained more positive charges. In general, the halophyte biochars had a higher ash content and lower point of zero net charge (PZNC) value, compared with the biochars derived from glycophytes, which would imply their higher potential value as an acidic soil conditioner.

Highlights

1. The biochar derived from *Suaeda salsa* had high ash and sodium salt.
2. The biochar derived from *Phragmites australis* had the largest specific surface area.
3. The biochar derived from *Kalidium foliatum* carried much higher negative charge.

Keywords Halophyte · Biochar · Structural elements · Mineral elements · Surface charges

1 Introduction

Halophytes including three categories of euhalophytes, recrotohalophytes, and pseudohalophytes are a group of plants that can complete their life cycle under highly saline conditions such as salt-affected soils. There are approximately 1560 species of hylophytes in the world and more than 500

species in China (Zhao et al. 2002). Most of the salt-affected soils, about 9.55×10^8 ha in the world and 9.91×10^7 ha in China, can well grow certain halophytes (Qadir et al. 2000; Zhao et al. 2002). There is therefore a huge volume of halophyte biomass produced in the salt-affected regions. Unfortunately, most of the halophyte biomass is not properly utilized though a tiny amount as animal forage (Ventura et al. 2015). It is thus meaningful to develop an innovative approach to properly use halophyte biomass.

Pyrolysis, among the ways to use halophyte biomass, has received particularly much attention in recent years. The products of both bio-oil and biogas can be directly used as fuel and industrial starting materials as well (Yue et al. 2016). The most interesting product, namely biochar, has a myriad of functions and can be used in industry, environment, and agriculture (Sohi et al. 2010). It is widely believed

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that the most attractive application of biochar may be as a soil conditioner (Kavitha et al. 2018). A remarkable volume of data have shown that biochar amendments can significantly improve soil physical, chemical, and even microbiological fertilities (Lehmann et al. 2011; Luo et al. 2012; Guo et al. 2019; Amoah-Antwi et al. 2020). Cereal productivity and root biomass are thereafter significantly enhanced due to biochar amendment (Hussain et al. 2017). Moreover, biochar amendment can play a pivotal role in enlarging soil carbon sequestration capacity and reducing greenhouse gas emissions as well (Liu et al. 2018). It is well documented that the properties of biochar directly determine its application and the effects. For example, wood-based biochar is suitable to be considered as a solid fuel and adsorbent (Zhang et al. 2017), while both fibrous and manure biochars may engender high impacts on soil quality (Shi et al. 2019; Han et al. 2017). It is, therefore, necessary to analyze and evaluate the properties of biochar before amending into soil.

It is well known that the characteristics of biochar depend on both feedstock and pyrolysis process (Chen et al. 2019). However, there is little knowledge of the biochars derived from different halophytes. Halophytes are diverse in botany, anatomy, and salt tolerance. Euhalophytes can absorb a large amount of salt from the environment and accumulate it in succulent tissue. The salt content is measured up to 43% of dry matter (Zhao et al. 2013a, b). The specific tissues like salt glands, salt bladders may influence the pore development during pyrolysis (Flowers et al. 2015). The specific nature of halophytes may affect not only the pyrolysis process but the biochar characteristics and applications as well (Mao et al. 2019).

In this study, five typical halophytes widely distributed in the arid regions of China were harvested and then slowly pyrolyzed in a fixed bed for 1 h. We hypothesized that the biochars derived from the five halophytes might have different characteristics and potential value as a soil conditioner considering their distinct botanic characteristics. The objectives of this study were to understand the specific characteristics of five halophyte biochars, and then evaluate their

particular potential value as a soil conditioner, compared with those from glycophytes.

2 Materials and methods

2.1 Feedstock

The selected five typical halophytes were three euhalophytes of *Suaeda altissima* (Linn.) Pall. (SA), *Suaeda salsa* (Linn.) Pall. (SS), and *Kalidium foliatum* (Pall.) Moq. (KF), one recretohalophyte of *Phragmites australis* (PA) and one pseudohalophyte of *Tamarix chinensis* Lour. (TC). The basic properties of the five halophytes are shown in Table 1.

2.2 Preparation of biochar

One hundred grams of halophyte dry matter (< 1 cm) was tightly compacted into a pyrolysis reactor with screw lids at both ends in which one was connected to a steel tube for N₂ gas flow. The reactors were placed in a muffle furnace (SX4-10, Shuli, China), heated to 500 °C at a rate of approximately 10 °C min⁻¹, and then maintained for 1 h. The whole pyrolysis process was performed under pure N₂ gas atmosphere (10psi). After cooling to room temperature, the biochars were collected and weighed to calculate the biochar yield. The biochar derived from the *Suaeda altissima* (Linn.) Pall., *Suaeda salsa* (Linn.) Pall., *Kalidium foliatum* (Pall.) Moq., *Phragmites australis*, and *Tamarix chinensis* Lour. were defined as B_{SA}, B_{SS}, B_{KF}, B_{PA}, and B_{TC}, respectively.

2.3 Analysis of biomass and biochar

The cellulose, hemicellulose, and lignin contents in the feedstocks were determined by the Van Soest method (Van Soest et al. 1991). The ash content was determined by heating at 550 °C for 4 h in a muffle furnace (Yue et al. 2017). The contents of carbon (C), hydrogen (H), and nitrogen (N) were measured with an elemental analyzer (Elementar

Table 1 The chemical properties of the five halophyte feedstocks

Feedstocks	Ash %	C	H	N	O	H/C _a	O/C _a	C/N _m	(O+N)/C _a	Hemicellulose %	Cellulose	Lignin
<i>Suaeda altissima</i> (SA)	5.92c	44.19b	6.60a	0.589 cd	42.26a	1.79b	0.717a	87.47ab	0.728a	25.84d	44.97a	9.47c
<i>Suaeda salsa</i> (SS)	7.71a	41.06d	6.20c	0.518d	36.62c	1.81a	0.669b	92.45a	0.680b	28.07c	36.46b	7.34d
<i>Kalidium foliatum</i> (KF)	6.40b	43.30c	6.53b	1.24a	38.76b	1.81a	0.671b	40.75d	0.696b	30.06b	32.16c	10.48b
<i>Phragmites australis</i> (PA)	8.18a	43.16c	6.32c	0.772b	38.79b	1.76c	0.674b	65.39c	0.689b	31.04a	36.88b	7.32d
<i>Tamarix chinensis</i> (TC)	2.50c	45.94a	6.53b	0.650c	34.58d	1.71d	0.564c	82.55b	0.576c	22.06e	36.96b	12.44a
Means	6.14	43.53	6.44	0.755	38.20	1.78	0.659	73.72	0.674	27.41	37.49	9.41

The H/C_a, O/C_a and (O+N)/C_a are the ratios among the atomic numbers of H, O, N and C. The C/N_m is the mass ratio between C and N. The different lower-case letters in the same line represent the significant difference at $p < 0.05$ among the different feedstocks

Analysensysteme GmbH, Hanau, Germany), while oxygen (O) content was calculated by the subtraction method [$O\% = 100\% - (H_2O\% + Ash\% + C\% + H\% + N\%)$] (Chen et al. 2019). Following extraction with distilled water at the ratio of 1:10 (w/v), the pH value of the extracts was determined using a UB-7 pH meter while EC was measured with a DDS-307A conductivity meter and dissolved organic carbon (DOC) was measured by TOC instrumentation (Elementar varioTOC, Germany). After digestion with sulfuric acid (H_2SO_4)-hydrogen peroxide (H_2O_2), the dissolved organic nitrogen (DON) of the extracts was determined by the Kjeldahl method, the dissolved organic phosphorus (DOP) by molybdenum antimony resistance colorimetry, potassium (K), calcium (Ca), sodium (Na), and magnesium (Mg) by inductively coupled plasma optical emission spectrometry (ICP-OES, Avio 200, Perkin-Elmer, USA).

The morphological characteristics of the biochars were observed with a scanning electron microscope (S-3400N, HITACHI, Japan). The pore structure was determined with a specific surface area analyzer (BK122T B, JWGB, China) according to the nitrogen adsorption-static volumetric method. The mesopores and macropores were calculated according to the method suggested by Barrett, Joyner and Halenda, while the micropores by the method of Saito and Foley (Zhao et al. 2014). The surface charge was measured by the ion adsorption exchange method (Cheng et al. 2008). The point of zero charge (PZNC) value was the pH value when the positive and negative charges were equal. The anion exchange capacity (AEC) was the amount of positive surface charge at pH 3.5. The cation exchange capacity (CEC) was the amount of negative surface charge at pH 7.0 (Cheng et al. 2008).

2.4 Statistical analysis

The differences in pyrolysis products prepared under different temperatures were compared through one-way analysis of variance and then expressed as the least significant

difference (LSD). A p -value < 0.05 was considered statistically significant.

3 Results and discussion

3.1 Yield

The five typical halophyte feedstocks had a similar biochar yield, ranging from 32.75 to 39.20%, under the slow pyrolysis process at 500 °C for 1 h (Table 2). The biochar yields of the halophyte feedstocks were close to those of the fibrous materials such as gramineous crop straws, while much lower than those of woody, animal manure, and sludge feedstocks (Hassan et al. 2020; Hopkins and Hawboldt, 2020). It is known that the large molecules in the feedstocks are broken and converted into small molecules during pyrolysis (Chen and Chen 2009). The yield of biochar is therefore dependent on the characteristics of the feedstock and the pyrolysis process. In a specific pyrolysis process, especially at a certain pyrolysis temperature, the yield of biochar is mainly decided by the characteristics of the feedstock. Zhao et al. (2013a, b) reported that the feedstocks with high ash and lignin contents often had a high yield in biochar. However, a weak relationship between the ash content in the feedstocks and biochar yield was found in this study ($r = 0.55$, $p > 0.05$). The carbon content of the halophytes was closely related to the biochar yield ($r = 0.83$, $p < 0.05$), which might imply that lignin content in the halophytes rather than the ash determined the biochar production.

3.2 Structural elements

The obtained biochars from the five typical halophytes had similar contents of structural elements, compared to those of glycophyte-derived biochars (Sun et al. 2013). They had higher C and N contents, 58.50–71.73% and 0.66–1.49% respectively, compared to the feedstocks (Table 2), which showed the relative enrichment of both C and N during

Table 2 The basic chemical properties of the biochars derived from five halophytes under 500 °C for 1 h

Biochar	Yield %	C	H	N	O	Ash	H/C _a	O/C _a	C/N _m	(O+N)/C _a
B _{SA}	32.75b	71.34b	4.25a	0.664d	6.03d	12.81c	0.715a	0.0634c	125.56a	0.0714c
B _{SS}	39.20a	58.50e	3.40c	0.915c	8.92b	23.64a	0.697b	0.114a	74.59bc	0.128a
B _{KF}	34.07b	65.08c	3.40c	1.49a	6.78cd	18.84b	0.626c	0.0781b	51.10d	0.0977b
B _{PA}	33.37b	61.21d	2.90d	1.03b	7.66bc	23.13a	0.569d	0.0938b	69.61c	0.108b
B _{TC}	33.05b	71.73a	3.76b	1.03b	11.81a	7.26d	0.629c	0.123a	81.32b	0.136a
Means	34.49	65.57	3.54	1.03	8.24	17.14	0.647	0.0946	80.44	0.108

The H/C_a, O/C_a and (O+N)/C_a are the ratios among the atomic numbers of H, O, N and C. The C/N_m is the mass ratio between C and N. The different lower-case letters in the same line represent the significant difference at $p < 0.05$ among the different biochars

pyrolysis. The significant positive correlation between the C and N in the feedstocks and their biochars ($r=0.90$, $p<0.01$) might imply that enrichments of both C and N in the biochars were proportional to those in the feedstocks. In contrast, both O and H contents in the biochars decreased from 34.58–42.26% to 6.03–11.81% and 6.20–6.60% to 2.90–4.25%, respectively, which indicated remarkable losses of both O and H during pyrolysis. The chemical reactions such as dehydration, dehydrogenation, deoxygenation, and decarboxylation occurring during pyrolysis can cause large changes in these structural elements, in which C is relatively enriched, while O reduced, with small changes in both H and N (Yue et al. 2017). In addition, the significant relationships of C vs lignin ($r=0.82$, $p<0.01$) and hemicellulose ($r=-0.75$, $p<0.01$), O and H vs hemicellulose ($r=-0.71$, -0.65 , respectively; $p<0.05$), H vs cellulose ($r=0.70$, $p<0.01$), and N vs cellulose ($r=-0.92$, $p<0.01$) might reveal the complicated reactions and changes during pyrolysis.

The atomic ratios of H/C_a , O/C_a and $(O+N)/C_a$ in the biochars decreased by 63%, 86%, and 84%, respectively, while the mass ratio of C/N_m increased by 9%, compared with those of the feedstocks. The values of H/C_a and C/N_m in the biochars were independent of those of feedstocks, while both O/C_a and $(O+N)/C_a$ ratios in the feedstocks negatively decided those in the biochars ($r=-0.83$, -0.84 , respectively, $p<0.01$). It was evident that O in the feedstocks might undergo deoxygenation and decarboxylation and thus result in a high loss of O (Calvelo Pereira et al. 2011). The means of H/C_a , O/C_a and $(O+N)/C_a$ and C/N_m in the halophyte-derived biochars were 0.65, 0.09, 0.11, and 80.44, respectively, which fell within the ranges of those from glycophytes (Wang et al. 2015). However, the low ratios of H/C_a , O/C_a and C/N_m of both B_{KF} and B_{PA} might indicate a high degree of aromatization and therefore a stable structure (Yan et al. 2012).

3.3 Mineral elements

It is widely known that biochar usually contains a certain amount of ash, showing alkalinity and high EC value since

the feedstock contains a certain number of mineral elements. Those minerals can be mostly remained in the biochar during the pyrolysis process (Shi et al. 2019). The halophyte-derived biochars in this study had variable contents in ash, EC, and pH values, ranging from 7.26–23.64%, 1.76–23.45 $mS\ cm^{-1}$ and PH 7.86–10.47, respectively. The ash content of the biochars was linearly related to that in the halophyte feedstocks ($r=0.97$, $p<0.01$). The biochars derived from euhalophytes, such as B_{SA} and B_{SS} , had much higher ash since they developed a compartmentalized vacuole structure for salt storage (Table 2). The glycophyte-derived biochar was reported to have ash content ranging from 2.28 to 37.3% (Zhang et al. 2017; Han et al. 2017), while that of biochars from manure and sludge was relatively high, 14.41–57.45% (Singh et al. 2010; Xiao et al. 2019). Generally, the ash content of the halophyte-derived biochars was higher than that of most glycophyte-derived biochars, but lower than that of manure and sludge biochars.

The halophyte-derived biochars had a diverse composition of minerals, dominated in Na (1.06–33.93 $g\ kg^{-1}$), followed by K (1.68–6.17 $g\ kg^{-1}$) (Table 3). The euhalophyte-derived biochars such as B_{SA} , B_{SS} , B_{KF} had relatively high contents of both Na and Mg, while the recretohalophyte biochar of B_{PA} was high in K, and pseudohalophyte biochar of B_{TC} high in Ca. It was obvious that halophyte-derived biochars had a comparable Na content with manure biochar (Subedi et al. 2015), but much higher than glycophyte-derived biochar (0.17–2.00 $mg\ kg^{-1}$) (Suliman et al. 2015).

The minerals as the main portion of the ash in biochar often exist as oxides, hydroxides, carbonates, phosphates and what like, which are assumed to be related to the pH and EC values in biochar (Hung et al. 2017; Piash et al. 2021). The ash percentage of the halophyte biochars was strongly related to the pH value ($r=0.84$, $p<0.05$) and K content ($r=0.94$, $p<0.01$), but weakly to EC value ($r=0.61$, $p>0.05$). The EC value was strongly dependent on Na content in the biochars ($r=0.99$, $p<0.01$), while the pH value was somewhat linked with K content ($r=0.69$, $n=4$) rather than Na content ($r=0.42$, $n=4$) in the biochars. Cantrell et al. (2011) measured that less than one-third of the ash could be dissolved in water,

Table 3 The pH, EC value and dissolved element content of the biochars derived from five halophytes under 500 °C for 1 h

Biochar	pH	EC ($mS\ cm^{-1}$)	Na ⁺ ($g\ kg^{-1}$)	K ⁺	Ca ²⁺	Mg ²⁺	DOC ($mg\ kg^{-1}$)	DON	DOP
B_{SA}	9.35 ± 0.50c	2.64 ± 0.78c	5.48 ± 0.12c	1.97 ± 0.01d	0.0146 ± 0.01d	0.981 ± 0.02c	3586.25 ± 0.24a	123.69 ± 0.02a	14.20 ± 0.10d
B_{SS}	9.77 ± 0.06bc	23.45 ± 4.61a	33.93 ± 0.56a	6.17 ± 0.02b	0.0303 ± 0.01c	1.20 ± 0.17b	3256.00 ± 0.15a	86.88 ± 0.02ab	94.04 ± 6.71a
B_{KF}	10.47 ± 0.17a	8.10 ± 1.15b	14.64 ± 0.09b	5.07 ± 0.07c	0.0237 ± 0.01 cd	1.62 ± 0.07a	3283.63 ± 0.01a	104.19 ± 0.00a	2.40 ± 0.00e
B_{PA}	10.07 ± 0.11ab	2.91 ± 0.56c	3.72 ± 0.24d	9.44 ± 0.08a	0.0945 ± 0.00b	0.323 ± 0.01d	886.69 ± 0.33b	58.94 ± 0.02b	41.19 ± 2.01c
B_{TC}	7.86 ± 0.12d	1.76 ± 0.25c	1.06 ± 0.00e	1.68 ± 0.04e	1.60 ± 0.03a	0.880 ± 0.05c	634.06 ± 0.02b	57.94 ± 0.01b	89.74 ± 4.02b
Means	9.5	7.77	13.82	5.08	0.416	1.00	2329.33	86.33	48.31

The different lower-case letters in the same line represent the significant difference at $p<0.05$ among the different biochars

which might explain the inconsistency of ash with EC value. Current data have shown that the ash composition in biochar is attributed to its liming effect in acid soils (Masud et al. 2020). Halophyte-derived biochars may therefore have a remarkable liming effect for their high ash content. However, the biochars should be checked for their high Na content which may cause a risk for some Na^+ -sensitive plants.

Remarkable amounts of dissolved organic carbon, nitrogen, and phosphorus (DOC, DON, DOP) were detected in the halophyte-derived biochars (Table 3), which fell within the ranges of those in glycophyte biochars (Wu et al. 2012). The biochars derived from euhalophytes, such as B_{SA} , B_{SS} , and B_{KF} , had higher dissolved organic carbon than the biochar from either recretohalophyte (B_{PA}) or pseudohalophyte (B_{TC}). The B_{SS} even had high DOP, 94.04 mg kg⁻¹. It was not certain whether more dissolved organic matter might be released during the pyrolysis process of euhalophyte. It is believed that the dissolved organic matter in biochar can be used as a substrate for microorganisms and thus influence the microbial activity and community structure as well (Luo et al. 2012). Some of the small molecules in biochar were reported to stimulate or inhibit plant growth (Yuan et al. 2021). It would be worthy of understanding the unique composition of the dissolved organic matter in halophyte-derived biochar and its impacts on soil microbes.

3.4 Pore structure

Biochar usually has a porous structure since the organic matter in the feedstock is gradually volatilized during the pyrolysis process. The porosity of biochar is therefore dependent on both feedstock and pyrolysis conditions such as temperature. However, the anatomical structure of the feedstock may largely decide the biochar porosity under-designed pyrolysis conditions (Lehmann et al. 2011). The obtained biochars in this study had distinct pore structures depending on the halophyte feedstocks (Fig. 1). Both B_{SA} and B_{SS} possessed mainly mesopores of 2–50 nm, and thus had higher values of porosity, mode pore diameter (MPD), and average pore size (APS). The biochars of B_{KF} , B_{PA} , and B_{TC} were dominant in 1–3 nm pores, and had low values of MPD and APS, while both the specific surface area (SSA) and pore volume were relatively large. Among the five biochars, B_{PA} had the largest SSA and pore volume (PV), 344.02 m² g⁻¹, and 0.24 cm³ g⁻¹, respectively (Table 3). Both feedstocks of *Suaeda altissima* and *Suaeda salsa* had an anatomical structure of salt compartmentalization, and might easily form columnar and cavity-like large pores. The feedstocks of *Phragmites australis* and *Tamarix chinensis* Lour. could readily develop fine and small pores for their uniform and dense anatomical structure (Figs. 2, 3). In particular, the biomass of *Phragmites australis* might be likely to form more pores for its well-developed vascular structure (Fig. 2).

Fig. 1 Distribution of pore volume in the biochars derived from five halophytes (B_{SA} *Suaeda altissima* biochar; B_{SS} *Suaeda salsa* biochar; B_{KF} *Kalidium foliatum* biochar; B_{PA} *Phragmites australis* biochar; B_{TC} *Tamarix chinensis* biochar)

Fig. 2 SEM images of the five halophyte feedstocks (SA *Suaeda altissima*; SS *Suaeda salsa*; KF *Kalidium foliatum*; PA *Phragmites australis*; TC *Tamarix chinensis*)

Fig. 3 SEM images of the biochars derived from five halophytes (B_{SA} *Suaeda altissima* biochar; B_{SS} *Suaeda salsa* biochar; B_{KF} *Kalidium foliatum* biochar; B_{PA} *Phragmites australis* biochar; B_{TC} *Tamarix chinensis* biochar)

A large number of data has shown that the biochar with a well-developed pore structure and the large SSA often has strong adsorption capacity for ions, polar and nonpolar substances as well (Yue et al. 2016). It can be thereafter used as the absorbent for removing heavy metals such as Pb^{2+} , Cd^{2+} ,

and Cu^{2+} ions (Kalinke et al. 2019). A few studies have reported that biochar amendments can significantly enhance soil water holding capacity (Liu et al. 2015) and nutrient ion retention capacity as well (Rajkovich et al. 2012). In addition, the micropores in biochar can provide habitats for

bacteria (0.3–3 μm) and even fungi (2.0–80 μm) and thus help them escape from predators (Luo et al. 2012). Further work may be required for exploring adsorption behaviors of the halophyte-derived biochars with unique pore structures in soil and water as well.

3.5 Surface charge

The obtained biochars were all rich in pH-dependent charges (Fig. 4). The positive charge gradually decreased with enhancing medium pH value. The positive charge of B_{SA} decreased from 260.92 to 133.78 cmol kg^{-1} when the pH value increased from 1 to 12 (Fig. 4a). The positive

charge in B_{PA} also increased to 149.780 cmol kg^{-1} though it was the lowest among the tested biochars (Fig. 4c). The negative charge, in contrast, increased with lifting pH value of the medium. The B_{SS} showed higher negative charge, 0.46–172.92 cmol kg^{-1} (Fig. 4b), while B_{PA} lower, 0.52–17.55 cmol kg^{-1} . Our results fell within the reported ranges of the surface charge (Yue et al. 2017; Chen et al. 2019).

The five halophyte-derived biochars had similar values of point of zero net charge (PZNC), pH 4.3–5.6 (Table 4), which might suggest the similarity in their charged functional groups. The low PZNC of the biochars probably

Fig. 4 The surface charges versus pH values for the biochars derived from *Suaeda altissima* (a); *Suaeda salsa* (b); *Kalidium foliatum* (c); *Phragmites australis* (d) and *Tamarix chinensis* (e)

Table 4 Pore structure parameters of the biochars derived from five halophytes under 500 °C for 1 h

Biochar	SSA (m ² g ⁻¹)	PV (cm ³ g ⁻¹)	APS (nm)	MPD (nm)	MMPS (nm)
B _{SA}	3.50 ± 2.36e	0.0135 ± 0.00e	19.17 ± 10.61a	18.80 ± 6.37b	1.26 ± 0.50a
B _{SS}	9.20 ± 4.21d	0.0279 ± 0.00d	12.13 ± 0.71b	19.25 ± 8.22a	0.941 ± 0.01c
B _{KF}	46.73 ± 18.05c	0.0670 ± 0.01c	5.11 ± 0.03c	9.67 ± 4.57c	1.16 ± 0.11b
B _{PA}	344.02 ± 32.10a	0.240 ± 0.11a	2.79 ± 0.01e	6.38 ± 0.07e	0.564 ± 0.02e
B _{TC}	153.64 ± 69.79b	0.0966 ± 0.03b	5.76 ± 2.75d	8.52 ± 2.05d	0.905 ± 0.06d
Means	111.42	0.0891	8.99	12.53	0.967

The different lower-case letters in the same line represent the significant difference at $p < 0.05$ among the different biochars

SSA specific surface area; PV pore volume; APS average pore size; MPD mode pore diameter; MMPS macro-pore median pore size

implied a high capacity to enhance negative charge under an alkaline environment.

Compared with other biochars, B_{SA} had much higher AEC_{pH3.5}, 16.99 cmol kg⁻¹, and might be suitable to remove the positively charged pollutants under acidic conditions (Table 5). In contrast, except for B_{SA}, other four biochars might have better adsorption capacity for negatively charged materials under alkaline conditions since they tended to have a high value of CEC_{pH7.0} 19.36 cmol kg⁻¹.

It is widely known that biochar usually contains a large number of pH-dependent charges regardless of the feedstock type. The negative charge is assumed to mainly come from functional groups such as hydroxyl and carboxyl groups. The positive charge may be stemmed from nitrogen-containing functional groups, surface oxygen-containing alkaline substances, such as amino, pyrone, or benzopyran, and from the electron-rich centers between graphite layers that attract protons in solution (Chen et al. 2019). It is not certain if the halophyte-derived biochars have similar characteristics as those from glycophyte feedstock. A few studies have shown that biochar amendment can significantly increase soil CEC, and thus improve soil nutrient retention capacity (Chen et al. 2018; Shi et al. 2019). However, we have little understanding in the roles of halophyte biochar as a soil amendment. It is thus meaningful to investigate the impacts of the halophyte-derived biochars on soil physicochemical properties.

4 Conclusion

The biochars derived from different halophytes had distinct characteristics depending on their anatomical features. The B_{SS} had higher sodium salt in ash, while B_{PA} was high in specific surface area. The B_{KF} had much negative charge, and a high CEC value, while B_{SA} carried more positive charge and had a high AEC_{pH3.5} value. Compared with biochars derived from glycophytes, the halophyte-derived biochars generally had higher ash and

Table 5 Surface charge parameters of the biochars derived from five halophytes under 500 °C for 1 h

Biochar	PZNC	AEC _{pH3.5} (cmol kg ⁻¹)	CEC _{pH7.0} (cmol kg ⁻¹)
B _{SA}	5.44 ± 0.02b	16.99 ± 0.21a	6.45 ± 0.02d
B _{SS}	4.26 ± 0.01e	3.80 ± 0.02e	9.89 ± 0.08b
B _{KF}	5.40 ± 0.01c	6.05 ± 0.03c	19.36 ± 0.13a
B _{PA}	5.59 ± 0.03a	9.30 ± 0.01b	5.90 ± 0.01e
B _{TC}	4.88 ± 0.02d	5.05 ± 0.01d	7.76 ± 0.00c
Means	5.11	8.24	9.87

The different lower-case letters in the same line represent the significant difference at $p < 0.05$ among the different biochars

PZNC point of zero net charge; AEC_{pH3.5} anion exchange capacity; CEC_{pH7.0} cation exchange capacity

lower PZNC value and might have a higher potential value as an acidic soil conditioner.

Acknowledgements This study was supported by the 13th five-year project of National Key Technology R&D Program (No. 2016YFC0501306-02), and implemented at Key Laboratory of Arable Land Conservation (North China), Ministry of Agriculture, Key Laboratory of Plant-Soil Interactions, Ministry of Education, China Agricultural University.

Authors' contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Hongyang Xiao, Qimei Lin and Jianzhong Li. The first draft of the manuscript was written by Hongyang Xiao. All authors contributed to the article and approved the submitted version.

Funding This study was supported by the National Key Research and Development Program of China (2016YFC0501306).

Availability of data and materials The datasets analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Conflict of interest The authors declared that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential competing interests.

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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