Wang *et al. Biochar* (2023) 5:21
https://doi.org/10.1007/s42773-023-00219-9

Biochar

PERSPECTIVE

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Salt-affected marginal lands: a solution for biochar production

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Abstract

The literature has shown that biochar can serve as potential amendment to achieve sustainable agriculture and environment. The accessibility and availability of cheap feedstock are considered as important constraint factors for the widespread application of biochar in agriculture. Marginal lands are widely distributed globally, several times larger than arable land, and hold little value for food production due to poor soil conditions. However, these lands are suitable for growing plants, which can be used as feedstock for biochar production. The salt-affected lands, as one of the main marginal lands, are particularly suitable for cultivating diverse varieties of halophytes that can be pyrolyzed into biochar, bio-gas, and bio-oil. The halophyte-derived biochar is useful to produce a desirable acid soil conditioner due to its high ash and rich bases, and improves soil characteristics under extreme saline conditions. Additionally, syngas and bio-oil hold potential benefits as fuels and industrial raw materials. This study introduces an innovative management technique for marginal lands such as salt-affected land, which can provide all-round benefits in food production, land management, vegetation coverage, carbon sequestration, and climate change mitigation.

Highlights

- Marginal lands such as salt-affected lands may supply adequate and cheap feedstock for biochar production.
- Biochar derived from halophytes can be befittingly used as a soil amendment, particularly for acidic soils.
- Halophyte biochar soil amendment can achieve all-wins in sustaining agriculture, ecology, and environment.

Keywords Marginal lands, Salt-affected soils, Halophytes, Biochar, Soil amendment

Handling Editor: Hailong Wang

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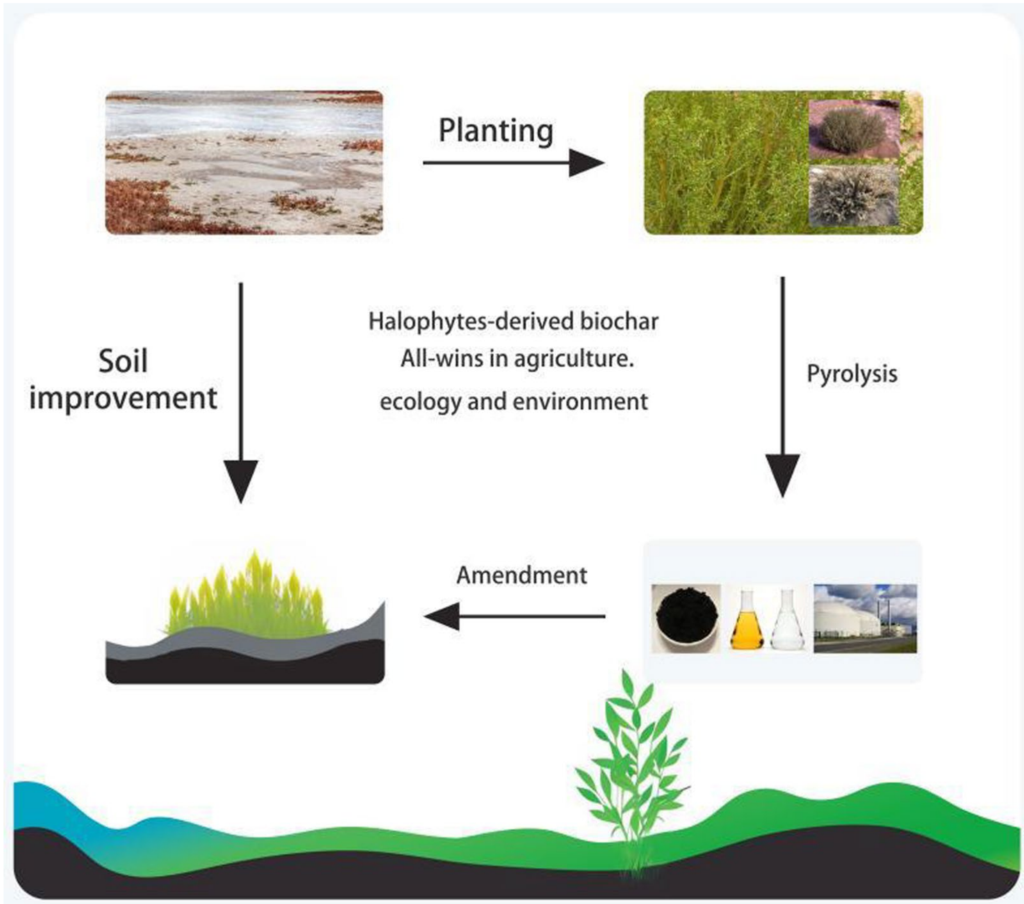
Graphical Abstract



1 Introduction

Marginal lands are economically characterized as low productivity lands under normal agricultural inputs (fertilization, irrigation, common tillage, weeding, and other agronomic measures). The net income generated from these lands may just compensate for the input or even lower than the incurred cost (Qaseem and Wu 2020). These lands usually have little or no agricultural value due to poor soil conditions including salinization, acidification, desertification, contamination, and low nutrients (Stephanie et al. 2013; Tilman et al. 2006). The tough climatic conditions like drought and cold and poor agricultural infrastructure also limit crop growth on these lands (Qaseem and Wu 2020).

The marginal lands in China constitute about 290 million ha, which is more than twice as much as the arable land (128 million ha). In China, arable land per capita is 0.09 ha, which is less than half of the global average. Constant rise in the utilization of arable land for developing infrastructure construction projects is challenging. According to the Third National Land Survey Main Data Bulletin, the average annual reduction in arable land in China was estimated to be about 0.75 million ha for the period 2009 to 2019 (National Land & Resources 2016). Therefore, it is a great challenge for Chinese government to maintain the minimum level of arable land at 120 million ha in the next few decades, a threshold set by the central government (Liu et al. 2015). Rational development and utilization of the marginal lands can be explored as one of the strategies to deal with the issue. Therefore, it is critically important for Chinese government to effectively manage the marginal lands, in order to deal with key strategic issues of both food security and ecological and environmental safety (Tang et al. 2010). This strategy can also be advantageous to expand the carbon pool capacity in marginal lands for their low carbon density (Wong et al. 2010), which may remarkably contribute to the ambitious goals of peaking carbon dioxide emissions and achieving carbon neutrality in 2030, which is the target year to achieve such goals. This study aims to explore the salt-affected land, a major type of marginal lands, which is readily grown with halophytes as biochar feedstock. The purpose of this study is to introduce a new approach to the extension of biochar soil amendment and effective management of marginal lands. Specifically, this study aims to clarify the importance and necessity of the ecological restoration and social benefits of the marginal lands with a particular focus on salt-affected land. We also put forward to an all-win means for effective management of the salt-affected marginal land with halophytes.

2 Soil salinization: a major constraint in marginal lands

Based on the natural conditions and economic value, marginal lands can be divided into different groups like shrub land, sparse forest land, grasslands with moderate/low coverage, bottomland, shoal, salt-affected land, and bare land (Table 1). Most of the marginal lands do not hold significant economic value and are not feasible to develop for agricultural production because of their small size, scattered distribution, poor soil fertility and environmental conditions (Qaseem and Wu 2020). Salt-affected lands are usually distributed in arid and semi-arid regions, accounting for about 950 million ha worldwide. According to the estimation, the proportion of these lands is increasing at an annual rate of 1–2% due to climatic changes, inappropriate irrigation, and farming measures (Rana et al. 2008; Wong et al. 2010).

China has 131 million ha of salt-affected land, which accounts for 4.3% of the marginal lands (Table 1). The salt-affected lands in China are usually divided into four types based on the soil salinity; Songnen Plain in northeast China is dominated by Na_2CO_3 and $NaHCO_3$; eastern coastal region is distributed with NaCl and $MgCl_2$; Huang-Huai-Hai Plain with NaCl, Na_2CO_3, and Na_2SO_4; and the regions of Heilongjiang, Jilin, Inner Mongolia, Xinjiang, Hebei, and Shandong with Na_2SO_4 (Du and Hu 2021).

Table 1 Main marginal lands in China

Land type	Areas (ha)	Proportion (%)
Shrub land	4.87×10^8	15.99
Sparse forest land	3.47×10^8	11.40
Moderate/low coverage grassland	2.00×10^9	65.68
Bottomland	5.90×10^5	0.02
Shoal	5.01×10^7	1.65
Salt-affected land	1.31×10^8	4.30
Bare land	2.93×10^7	0.96

The data set is provided by National Tibetan Plateau Data Center (http://data.tpdc.ac.cn)

Salt-affected lands are mostly prevalent in the coastal, arid, and semi-arid regions of northwestern China. The Yellow River Delta is a typical coastal salt-affected area in northern China. The saline-alkali lands are mainly distributed in the inland regions of northeast and south China (Cao et al. 2021). In some provinces such as Xinjiang, Gansu, and Ningxia regions, the salt-affected lands are continuously expanding at an annual rate of 1% due to inappropriate irrigation practices (Li and Wang 2018). The Songnen Plain in northeastern China, a typical example, had only 2.4 million ha of saline land in the 1950s, which reached up to 3.9 milloin ha in 2016.

Since earlier 1990s, developed countries like the United States have achieved outstanding progress in improving salt-affected lands for agriculture production (McKell et al. 1986; Shih and Myhre 1994; Tanji et al. 1972). In contrast, in the countries like China with very limited arable land resources, the initial consideration must be to transform the salt-affected land into arable land to produce grain, oil, and fiber (Qaseem and Wu 2020; Tang et al. 2010; Wicke et al. 2011). Since the mid-twentieth century, China has made significant progress in the large-scale development and utilization of the salt-affected land in the regions of Huang-Huai-Hai River Basin (Shi 2003), Hetao region (Dong et al. 2019), and the inland of northwest China (Huang et al. 2022). The salt-affected lands in these regions have now transformed into an important base for producing grain, oil, cotton, fruit, and vegetables (Zhang 2014).

The remaining salt-affected lands, accounting for about 52% of the total marginal land in China, fall into tough natural and geographic conditions such as high dryness coefficient, low-lying terrain, and poor drainage (Shrivastava and Kumar 2015). Therefore, it is difficult and costly to produce food and bioenergy crops on these types of primary saline-affected lands (Qaseem and Wu 2020). This is particularly due to the huge consumption of freshwater in saline lands to cultivate crops. For instance, in the saline lands of the Hetao region, more than 1 m^3 of freshwater from the Yellow River is required to produce one-kilogram rice (Duan and Zhang 2000; Qiu et al. 2015). This is, therefore, impracticable in the countries like China with limited freshwater resources standing at 2300 cm^3 per capita, less than one-fourth of the global average (Qin et al. 2019). Furthermore, the salt-affected land has readily suffered from serious secondary soil salinization, with high ecological and environmental risks. Furthermore, the salt-affected land also suffer from secondary soil salinization, with high ecological and environmental risks. For example, the desertification of Minqin Oasis (Gansu Province, China) is alarming as the landscape of these areas turned into a desert when it was cultivated with glycophytes of cereals, cotton, and maize (Shi 2000).

Human society is facing the greatest challenges of the time in terms of achieving food security and eco-environmental safety. The availability of land and water resources on marginal lands is intrinsically linked to these global issues, but their exploitation for food production may cause severe ecological disasters. Therefore, it has become urgent to take innovative measures for proper management of the marginal lands, of which a major part constitutes of salt-affected lands in many countries like China.

3 Halophyte cultivation: the most natural approach to manage salt-affected lands

Numerous measures have been recommended to improve the quality of the salt-affected lands (Huang et al. 2022; Liu and Wang 2021; Sun et al. 2022). Hydraulic facilities are the most common and effective measure to reduce salinity and irrigate crops if abundant freshwater resources are available (Amini et al. 2016; Wang and Zhou 2013). Calcium-containing materials such as desulfurized gypsum can effectively replace sodium ions (Na^{+}) with calcium ions (Ca^{2+}) and then organic amendments are incorporated to enhance soil fertility and stabilize the soil structure (Gupta and Abrol 1990; Gharaibeh et al. 2009, 2010, 2011). Another effective measure can be phyto-reclamation, in which halophytes are used to remediate soil salinity (Devi et al. 2019; Mirza et al. 2014; Rozema and Schat 2013).

Halophytes have demonstrated their high tolerance under extremely saline conditions even higher than 200 mmol L^{-1} NaCl (Abbas et al. 1992; Glenn et al. 1999; Rozema and Schat 2013). More than 1560 halophyte species from 10 families have been documented around the world, including 500 species recorded in China (Glenn et al. 1999). They are often classified into three types of euhalophytes (true halophytes), recretohalophytes (salt excretors), and pseudohalophytes (salt avoiders) (Glenn et al. 1999) according to their physiological mechanisms of salt-tolerance. Generally, euhalophytes are a class with succulent leaves and stems that can store salts within vacuoles (Liu and Wang 2021). Recretohalophytes can actively expel salts from plant tissues through their unique structures like salt glands and salt sacs (Yuan et al. 2016). Pseudohalophytes can prevent salt from entering cells (Aslam et al. 2011). The common halophytes in China include *Suaeda altissima*, *Suaeda altissima (L.) Pall.*, *Kalidium foliatum (Pall.) Moq.*, *Phragmites australis*, *Tamarix chinensis Lour.*, *Phragmites australis (Cav.) Trin. ex Steud*, etc. (Xiao et al. 2022).

There is abundant literature available citing the numerous functions of halophytes depending on their botanic nature. Some halophytes such as *Atriplex patens*, *Kalidium foliatum (Pall.) Moq.* and *Salicornia europaea L.* can serve as forage (Al-Amro et al. 2019; Alkhuzai et al. 2015; Esfahan et al., 2010; Ghazanfar, 1999; Shamsi et al., 2020). The young leaves of *Lycium barbarum L.* and *Suaeda salsa (L.) Pall.* are edible for human consumption due to rich dietary fiber, vitamins, protein, and minerals (Al-Amro et al. 2019; Alkhuzai et al. 2015; Ghazanfar 1999). The seeds of *Salicornia europaea L.* contain a high percentage of oil and have the potential to produce biodiesel. *Apocynum venetumL.* and *Suaeda vermiculata* are valuable as herbs for their richness in flavonoids and conjugated linoleic acids (Abbas and El-Oqlah 1992; Al-Amro et al. 2019; Alkhuzai et al. 2015; Esfahan et al. 2010; Shamsi et al. 2020). Both *Apocynum lancifolium* and *reed* can be used as papermaking materials (Hamidov et al. 2007; Liu and Wang 2021; Mirza et al. 2014), while both *Tamarix chinensis* and *Iris lactea Pall* are widely used as urban green plants in western China.

Most euhalophytes have evolved with succulent stems and leaves, which can store a large amount of salts in a compartmentalized manner. The dry matter of these euhalophytes often has an ash content as high as 34%. A study has reported that during a four-month experiment, a large amount of salts, 504 kg ha^{-1} for *S. maritima*, and 474 kg ha^{-1} for *Sesuvium portulacastrum* can be removed annually from the extremely saline lands by harvesting the dry matter of euhalophytes (Ravindran et al. 2007). By cultivating the halophytes, soil salinity is gradually reduced and healthier crops can grow in less saline environments assuming the salt quantity added from irrigation water must be much lower than that removed by halophyte harvest. Tian et al. (2021) has conducted multi-year experiments on salt-affected soils in Kashgar (Xinjiang Autonomous Region, China) and reported that more than 400 kg of salts per hectare could be removed seasonally using euhalophytes. Soil salinity was reduced by 40%, 60%, and 85 to 90% in the first, second, and third years, respectively, and was finally suitable to cultivate glycophytes of most crop species.

Halophytes often have well-developed roots, supply a remarkable number of residues, and enhance the organic matter content in the salt-affected soil, which is extremely low under saline conditions (Wong et al. 2010; Xiao et al. 2022). The most popular halophytes are leguminous plants such as *Melilotus miller* and *Vicia villosa Roth*, which accelerate soil desalination and improve the soil organic matter content and minerals. Halophytes offer great potential to enhance organic carbon pools in salt-affected lands. Additionally, halophyte cultivation can greatly increase the vegetation coverage of land affected by saline conditions, which improves the ecological and environmental conditions for local inhabitants (Hasanuzzaman et al. 2014). The cultivation of halophytes could increase farmers income. Therefore, it is suggested that halophyte cultivation can be an economical, feasible, and sustainable approach to manage the under-utilized salt-affected lands in China (Behera and Ramachandran 2021; Jing et al. 2019; Liu and Wang 2021). The potential use of halophyte resources and extending the innovative technology for phytoreclamation is essential to remediate the salt-affected land.

4 Biochar derived from halophytes as soil amendment can achieve all-win outcomes

Biochar is a fine-grained, porous, and carbon-rich material obtained by pyrolyzing biomass under oxygen-limited conditions (Lehmann and Joseph 2015). It has been demonstrated through several pot and field trials, that biochar-amended soil in tropical and subtropical regions can significantly improve soil physical, chemical, and microbiological properties (Jeffery et al. 2017). The biochar-amended soil usually has lower bulk density, higher aggregates, porosity, water infiltration rate, water holding capacity, and available water content. However, these benefits may vary depending on the conditions of soil, the nature of biochar, and its rate of application (Chen et al. 2019; Fan et al. 2020; Joseph et al. 2021; Li et al. 2018; Schmidt et al. 2021; Shaaban et al. 2018; Xu et al. 2021).

Commonly, biochar amendment distinctly improves acidic soil by increasing pH value and reducing aluminum toxicity (Joseph et al. 2021; Wang et al. 2018; Wu et al. 2018; Zhu et al. 2017). However, biochar with low pH has also improved the quality of saline-alkali soil (Saifullah et al. 2018). Biochar amendment in addition to improving minerals content such as phosphorus, potassium, calcium, magnesium, etc. (Dai et al. 2020; Sheng and Zhu 2018; Joseph et al. 2021), also improves soil cation exchange capacity (CEC) (Joseph et al. 2021). Data from a few studies have proved that addition of biochar increases microbial biomass and activity in soils, and even changes the structure of its microbial community (Dai et al. 2018; Luo et al. 2013; Wu et al. 2019; Zhou et al. 2019a, b). The production of cereals, roots, and stems has all been reported to benefit from biochar amendment, with varying rates depending on crop, climate, soil, and the nature of biochar used (Hagemann et al. 2017; Kloss et al. 2014; Mao et al. 2012; Novak et al. 2009).

Existing studies show that biochar is useful in remediating the contaminated soils as it can reduce the bioavailability and mobility of heavy metals, and accelerate the degradation of pesticides, pigments, and petroleum

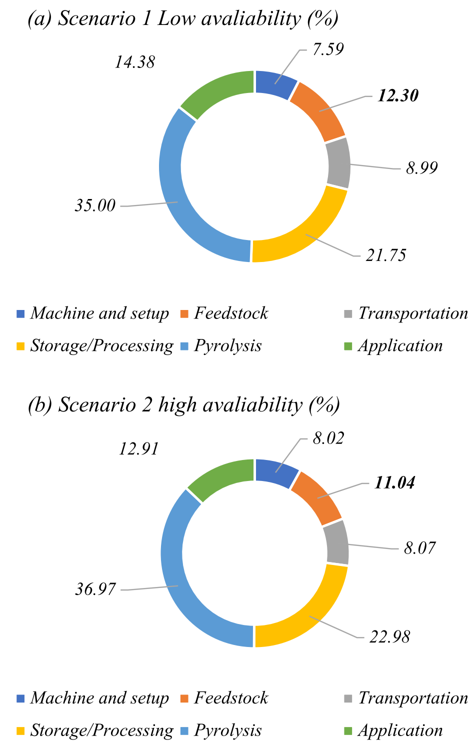


Fig. 1 The cost assessment (%) of biochar in the life cycle. **a** Scenario 1 is the low availability of feedstock and land application. The distance of the feedstock and land application (50 t ha^{-1}) is within 300 km. **b** Scenario 2 is the high availability of feedstock and land application. The distance of the feedstock and land application (50 t ha^{-1}) is within 100 km. (modified from Homagain et al. 2016)

(Ahmad et al. 2014; Fang et al. 2014; Qi et al. 2017; Safari et al. 2019). Additional benefits of biochar amendment are its ability to lock up carbon within soil pedon and reducing CH_4 and N_2O emissions (Duan et al. 2018; Liu et al. 2019; Luo et al. 2011; Nan et al. 2022). As a result, biochar soil amendment is considered a zero net carbon or even negative carbon strategy for sustainable agricultural development (Arneth et al. 2019; Buss et al. 2022; Lehmann et al. 2020, 2021).

However, despite these benefits, large scale adoption of biochar is challenging due to its high cost, as well as technical imperfections in biochar production. At present, one ton of biochar costs more than 300 US dollars in Chinese markets, far higher than the increased income of agricultural products. Utilizing, cheap feedstock may help to bring down these costs, since feedstock accounts for more than 11% of biochar cost (Fig. 1). Similarly, most of the organic wastes, like crop straw, sawdust, manure, and sludge can also be potentially used as feedstock for producing biochar through either slow or fast pyrolysis (Ippolito et al. 2020). Crop straw among these is highly suitable for biochar production since as feedstock, however, cannot be used for large-scale biochar production since as it is already directly incorporated into soil in China and other countries as well. It is therefore evident that abundant and cheap feedstock is an important prerequisite and significant limitation for large scale application of biochar in agriculture.

It may be feasible to have ample and cheap biochar feedstock from marginal lands such as salt-affected land (Fig. 2). For example, it is well known that halophytes can grow very well in most of the salt-affected lands (Xiao et al. 2022), and can be harvested each season from land containing more than 10% soluble salts without much additional investment (Al-Azzawi and Flowers 2022; Behera and Ramachandran 2021; Hasanuzzaman et al. 2014; Liu and Wang 2021). Our previous results showed that the typical halophytes could be used to derive 23–47% biochar, 18–37% biogas, and 27–53% bio-oil under a fixed-bed slow pyrolysis process for 2 h (Irfan et al. 2016a, b; Yue et al. 2016a, b). Both biochar and bio-oil have a certain calorific value, for example, biogas contains rich combustible gases, such as CO and H_2 that can account for 20–80% of the total and therefore, both biogas and bio-oil produced during the halophyte-derived biochar production process can also be used as direct fuel and industrial raw materials (Table 2).

Limited data so far have shown that halophyte-derived biochar, unlike glycophytes-derived biochar, has some special properties such as a higher ash content (up to 23.64%), more Na^+ (33.93 g kg^{-1}), and lower point of zero net charge value (Xiao et al. 2022). Pot trials have shown that amending the halophyte biochar helps to improve salt-affected soil and plant growth (Irfan 2016c; Yue 2017). Moreover, halophyte biochar may have many advantages as a conditioner of highly-weathered oxisols for their high ash and rich minerals such as sodium, potassium and magnesium. The rich ash can have a distinct liming effect, while the base metals may enhance the base saturation of the highly weathered acidic soil (Xiao 2021). Particularly, the luxuriant sodium in the halophyte biochar may partially act as potassium and benefit sodium-loving crops such as turnip and spinach. There are potentially all-round benefits from the halophytes-derived biochar production processes, which can then be useful to amended local saline soil or the highly weathered acid soil.

During recent decades, glycophyte-derived biochars, such as crop straw, sawdust, wood, etc. have received greater attention, which has resulted in remarkable progress in improving the manufacturing process of biochar. This enhances our understanding of its nature and impacts on soils and crops. However, there are still important knowledge gaps in halophyte-derived biochar that could help us gain potentially multiple benefits from halophytes.

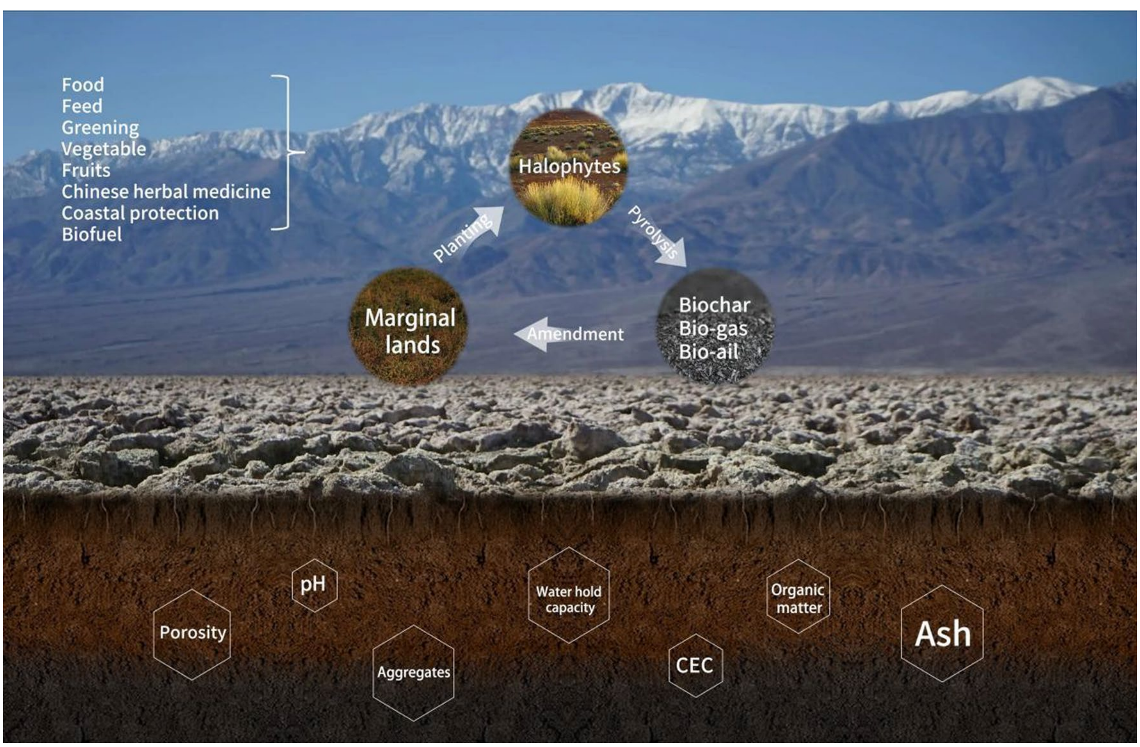


Fig. 2 Schematic diagram of comprehensive benefits of biochar derived from halophyte for marginal lands amendment

Table 2 The outputs of bio-oil, bio-gas, and biochar derived from typical halophytes under 300 °C, 500 °C, and 700 °C for 2 h in a fixed bed pyrolysis system

Halophytes	Temperature (°C)	Yield (%)			Heat value (MJ kg^{-1})		
		Biochar	Bio-gas[a]	Bio-oil	Biochar	Bio-gas[a]	Bio-oil
Achnatherum splendens L.	300	46	18	36	23	54	28
	500	34	25	41	23	68	27
	700	24	23	53	22	79	25
Tamarix chinensis	300	41	18	41	27	43	30
	500	26	30	44	28	80	28
	700	23	33	44	28	71	26
Salsola collina Pall.	300	47	26	27	19	20	29
	500	33	37	30	18	30	21
	700	26	27	47	17	31	20

[a] Bio-gas is the volume percentage of combustible gas in the total gases

5 Further research

Biochar-based soil amendment has multiple benefits for both agricultural and environmental applications. However, readily accessible and cheap feedstocks can be one of the important constraint factors for the widespread application of biochar in agriculture. The vast marginal lands, such as saline-alkali land widely distributed worldwide, offer a sustainable solution for biochar production. Further research can be as follows:

1) Most of the marginal lands are located in fragile ecosystems with poor soil and natural conditions. It is a great challenge to establish a native vegetation system in marginal lands that meets the requirements to sustain an ecological environment. Contemporary technology involving the use of genetic engineering to reestablish the ecosystem by maintaining biological diversity, stability, and sustainability in above, and below the marginal lands.
2) The sustainable development of marginal land ecosystems largely relies on the effective management of above-ground biomass resources. It is necessary to develop innovative techniques to build a stable value chain and industry chain for biomass-derived products. Much concern should be focused on the development of biochar-based poly-generation technology with marginal land biomass such as halophytes.
3) Marginal lands are characterized by low carbon density with low agricultural and ecological potential. Much attention should be paid to enhance soil organic matter content and carbon sequestration, and reduce greenhouse gas emissions. Further research is required to understand the processes, mechanisms and functions of biochar-derived carbon cycling in different terrestrial ecosystems.
4) It is particularly important for developing countries like China to maintain sufficient arable land to maintain self-sufficiency and guarantee food security. It is suggested to adopt compensating the arable land occupation with marginal lands as a national strategy for social and economic development. It is also realistic to improve the productivity of arable lands using halophyte biochar-based techniques, coupled with the National projects dealing with arable land construction. Mutual benefits obtained from both marginal and arable lands should be evaluated when the biochar-based amendment is applied on a large-scale.

Acknowledgements
Not applicable.

Author contribution
All authors contributed to the perspective conception and design. Material preparation, data collection and analysis were performed by YW, QL and JS. The first draft of the manuscript was written by YW and commented by ZL, KL, XW on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding
This work was supported by Inner Mongolia Autonomous Region Research Project: "Rejuvenating the Inner mongolia with Science and Technology" (Grant numbers 2021EEDSCXSFQZD011).

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

Declarations

Competing interests
All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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Received: 20 October 2022 Revised: 8 March 2023 Accepted: 14 March 2023
Published online: 07 April 2023

References

Abbas JA, El-Oqlah AA (1992) Distribution and communities of halophytic plants in Bahrain. J Arid Environ 22(3):205–218
Ahmad M, Rajapaksha AU, Lim JE, Zhang M, Bolan N, Mohan D, Vithanage M, Lee SS, Ok YS (2014) Biochar as a sorbent for contaminant management in soil and water: a review. Chemosphere 99:19–33
Al-Amro AM, El-Sheikh MA, El-Sheikh AM (2019) Vegetation analysis of some wetland habitats in central region of Saudi Arabia. Appl Ecol Environ Res 16:3255–3269
Al-Azzawi MJ, Flowers TJ (2022) Distribution and potential uses of Halophytes within the Gulf Cooperation Council States. Agronomy 12(5):1030
Alkhuzai JA, Freije AM (2015) Is 5-aminolevulinic acid concentration in plants related to soil salinity? A test with 17 native species of Bahrain. J Arid Environ 119:56–60
Amini S, Ghadiri H, Chen C, Marschner P (2016) Salt-affected soils reclamation carbon dynamics and biochar: a review. J Soils Sediments 16(3):939–953
Arneth A, Barbosa H, Benton TG, Calvin K, Pereira JP (2019) Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (pp. 1–98). Intergovernmental Panel on Climate Change (IPCC) Special Report
Aslam R, Bostan N, Nabgha EA, Maria M, Safdar W (2011) A critical review on halophytes: Salt tolerant plants. J Med Plants Res 5:7108–7118
Behera SS, Ramachandran S (2021) Potential uses of halophytes for biofuel production: opportunities and challenges. Sustainable biofuels, opportunities and challenges applied biotechnology reviews:. pp 425–448. https://doi.org/10.1016/B978-0-12-820297-5.00015-3
Buss W, Wurzer C, Manning DAC, Rohling EJ, Borevitz J, Mašek O (2022) Mineral-enriched biochar delivers enhanced nutrient recovery and carbon dioxide removal. Commun Earth Environ 3(1):67
Cao XF, Sun B, Chen HB, Zhou JM, Song XW, Liu XJ, Deng XD, Li XJ, Zhao YG, Zhang JB, Li JY (2021) Approaches and research progresses of marginal land productivity expansion and ecological benefit improvement in China. BCAS 36(3):336–348
Chen W, Meng J, Han X, Lan Y, Zhang W (2019) Past present and future of biochar. Biochar 1(1):75–87
Dai Z, Enders A, Rodrigues JL, Hanley KL, Brookes PC, Xu J, Lehmann J (2018) Soil fungal taxonomic and functional community composition as affected by biochar properties. Soil Biol Biochem 126:159–167
Dai Y, Zheng H, Jiang Z, Xing B, Jiang Z (2020) Combined effects of biochar properties and soil conditions on plant growth: a meta-analysis. Sci Total Environ 713:136635
Devi S, Kumar A, Arya SS, Kumari A, Pooja (2019) Economic utilization and potential of Halophytes. In: Hasanuzzaman M, Nahar K, Öztürk M (eds) Ecophysiology, Abiotic stress responses and utilization of Halophytes. Springer, Singapore. https://doi.org/10.1007/978-981-13-3762-8_9
Dong X, Li M, Lin Q, Li G, Zhao X (2019) Soil Na^+ concentration controls salt-affected soil organic matter components in Hetao region China. J Soils Sediments 19(3):1120–1129
Du XJ, Hu SW (2021) Research progress of saline-alkali land at home and abroad over the past 30 years based on bibliometric analysis. J Anhui Agric Sci 49(18):236–239
Duan AW, Zhang JY (2000) Water Use Efficiency of Grain crops in Irrigated Farmland in China. Trans the CSAE16(4):41–44
Duan P, Zhang X, Zhang Q, Wu Z, Xiong Z (2018) Field-aged biochar stimulated N_2O production from greenhouse vegetable production soils by nitrification and denitrification. Sci Total Environ 642:1303–1310
Esfahan EZ, Assareh MH, Jafari AA, Javadi SA, Karimi (2010) Phenological effects on forage quality of two halophyte species Atriplex leucoclada and Suaeda vermiculata in four saline rangelands of Iran. J Food Agric Environ 8(3–4):999–1003
Fan S, Zuo J, Dong H (2020) Changes in soil properties and bacterial community composition with biochar amendment after six years. Agronomy-Basel 10(5):746
Fang G, Gao J, Liu C, Dionysiou DD, Wang Y, Zhou D (2014) Key role of persistent free radicals in hydrogen peroxide activation by biochar: implications to organic contaminant degradation. Environ Sci Technol 48(3):1902–1910
Gharaibeh MA, Eltaif NI, Shunnar OF (2009) Leaching and reclamation of calcareous saline-sodic soil by moderately saline and moderate-SAR water using gypsum and calcium chloride. J Plant Nutr Soil Sci 172(5):713–719
Gharaibeh MA, Eltaif NI, Shraah SH (2010) Reclamation of a calcareous saline-sodic soil using phosphoric acid and by-product gypsum. Soil Use Manage 26(2):141–148
Gharaibeh MA, Eltaif NI, Albalasmeh AA (2011) Reclamation of highly calcareous saline sodic soil using Atriplex Halimus and by-product gypsum. Int J Phytoremediat 13(9):873–883
Ghazanfar SA (1999) Coastal vegetation of oman. Estuar Coast Shelf Sci 49(supp–S1):21–27
Glenn EP, Brown JJ, Blumwald E (1999) Salt tolerance and crop potential of halophytes. Crit Rev Plant Sci 18(2):227–255
Gupta RK, Abrol I (1990) Salt-affected soils: their reclamation and management for crop production. Adv Soil Sci 11:223–288
Hagemann N, Joseph S, Schmidt HP, Kammann CI, Harter J, Borch T, Young RB, Varga K, Taherymoosavi S, Elliott KW (2017) Organic coating on biochar explains its nutrient retention and stimulation of soil fertility. Nat Commun 8(1):1089
Hamidov A, Beltro J, Neves A, Khaydarova V, Khamidov M (2007) Apocynum lancifolium and chenopodium album - potential species to remediate saline soils. WSEAS Trans Environ Dev 3(7):123–128
Hasanuzzaman M, Nahar K, Alam M, Bhowmik P, Hossain A, Rahman M, Majeti P, Ozturk M, Fujita M (2014) Potential use of halophytes to remediate saline soils. Biomed Res Int 589341
Huang L, Liu Y, Ferreira JF, Wang M, Na J, Huang J, Liang Z (2022) Long-term combined effects of tillage and rice cultivation with phosphogypsum or farmyard manure on the concentration of salts minerals and heavy metals of saline-sodic paddy fields in Northeast China. Soil Tillage Res 215:105222
Ippolito JA, Cui L, Kammann C, Wrage-Mönnig N, Estavillo JM, Fuertes-Mendizabal T, Cayuela ML, Sigua G, Novak J, Spokas K, Borchard N (2020) Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. Biochar 2(4):421–438
Irfan M, Chen Q, Yue Y, Pang R, Lin QM, Zhao XR, Chen H (2016a) Co-production of biochar bio-oil and syngas from halophyte grass (*Achnatherum splendens* L) under three different pyrolysis temperatures. Bioresour Technol 211:457–463
Irfan M, Lin QM, Yue Y, Ruan X, Chen Q, Zhao XR, Dong XL (2016b) Co-production of biochar bio-oil and syngas from tamarix chinensis biomass under three different pyrolysis temperatures. Bio Resour 11(4):8929–8940
Irfan M (2016c) The characters of biochar and application in saline soil improvement. Thesis, China Agricultural University, Beijing
Jeffery S, Abalos D, Prodana M, Bastos AC, Van Groenigen JW, Hungate BA, Verheijen F (2017) Biochar boosts tropical but not temperate crop yields. Environ Res Lett 12(5):053001
Jing C, Xu Z, Zou P, Tang Q, Li Y, You X, Zhang C (2019) Coastal halophytes alter properties and microbial community structure of the saline soils in the Yellow River Delta China. Appl Soil Ecol 134:1–7
Joseph S, Cowie AL, Van ZL, Bolan N, Budai A, Buss W, Cayuela ML, Graber ER, Ippolito JA, Kuzyakov Y, Luo Y, Ok YS, Palansooriya KN, Shepherd J, Stephens S, Weng Z, Lehmann J (2021) How biochar works and when it doesn't: a review of mechanisms controlling soil and plant responses to biochar. GCB Bioenergy 13(11):1731–1764
Kloss S, Zehetner F, Wimmer B, Buecker J, Rempt F, Soja G (2014) Biochar application to temperate soils: Effects on soil fertility and crop growth under greenhouse conditions. J Plant Nutr Soil Sci 177(1):3–15

Lehmann J, Joseph S (2015) Biochar for environmental management: science technology and implementation. Sci Technol Earthsc 25(1):15801–15811
Lehmann J, Bossio DA, Kgel-Knabner I, Rillig MC (2020) The concept and future prospects of soil health. Nat Rev Earth Environ 1(10):1–10
Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, Cayuela ML, Camps-Arbestain M, Whitman T (2021) Biochar in climate change mitigation. Nat Geosci 14(12):883–892
Li JY, Wang JM (2018) Integrated life cycle assessment of improving saline-sodic soil with flue gas desulfurization gypsum. J Clean Prod 202:332–341
Li YF, Hu SD, Chen JH, Mueller K, Li YC, Fu WJ, Lin ZW, Wang HL (2018) Effects of biochar application in forest ecosystems on soil properties and greenhouse gas emissions: a review. J Soils Sediments 18(2):546–563
Liu LL, Wang BS (2021) Protection of Halophytes and their uses for cultivation of saline-alkali soil in China. Biology-Basel 10(5):353
Liu T, Liu H, Qi YJ (2015) Construction land expansion and cultivated land protection in urbanizing China: insights from national land surveys, 1996–2006. Habitat Int 46:13–22
Liu Q, Liu BJ, Zhang YH, Hu TL, Lin ZB, Liu G, Wang XJ, Ma J, Wang H, Jin HY, Ambus P, Amonette JE, Xie ZB (2019) Biochar application as a tool to decrease soil nitrogen losses (NH_3 volatilization N_2O emissions and N leaching) from croplands: options and mitigation strength in a global perspective. Global Change Biol 25(6):2077–2093
Luo Y, Durenkamp M, Nobili M, Lin Q, Brookes PC (2011) Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. Soil Biol Biochem 43(11):2304–2314
Luo Y, Durenkamp M, De NM, Lin Q, Devonshire BJ, Brookes PC (2013) Microbial biomass growth following incorporation of biochars produced at 350 °C or 700 °C in a silty-clay loam soil of high and low pH. Soil Biol Biochem 57:513–523
Mao JD, Johnson RL, Lehmann J, Olk DC, Neves EG, Thompson ML, Schmidt-Rohr K (2012) Abundant and stable char residues in soils: implications for soil fertility and carbon sequestration. Environ Sci Technol 46(17):9571–9576
McKell CM, Goodin JR, Jefferies RL (1986) Saline land of the United States of America and Canada. Reclam Revegetation Res 5(1–3):159–165
Mirza H, Kamrun N, Mahabub MA, Prasanta CB, Amzad MH (2014) Potential use of halophytes to remediate saline soils. Biomed Res Int 589341
Nan Q, Fang C, Cheng L, Wang H, Wu W (2022) Elevation of NO_3-N from biochar amendment facilitates mitigating paddy CH_4 emission stably over seven years. Environ Pollut 295:118707
National Land & Resources (2016) Ministry of Natural Resources of the People's Republic of China. https://www.mnr.gov.cn/sj/tjgb/201807/P020180704391918680508.pdf
Novak JM, Busscher WJ, Laird DL, Ahmedna M, Watts DW, Niandou MAS (2009) Impact of Biochar Amendment on Fertility of a Southeastern Coastal Plain Soil. Soil Sci 174(2):105–112
Qaseem MF, Wu A (2020) Marginal lands for bioenergy in China: an outlook in status, potential and management. GCB Bioenergy 13:21–44. https://doi.org/10.1111/gcbb.12770
Qi FJ, Kuppusamy S, Naidu R, Bolan NS, Ok YS, Lamb D, Li YB, Yu LB, Semple KT, Wang HL (2017) Pyrogenic carbon and its role in contaminant immobilization in soils. Crit Rev Environ Sci Technol 47(10):795–876
Qin X, Sun C, Han Q, Zou W (2019) Grey water footprint assessment from the perspective of water pollution sources: a case study of China. Water Res 46(3):454–465
Qiu KB, Cheng JF, Jia BQ (2015) Spatio-temporal distribution of cropland water use efficiency and influential factors in middle and east of China. Trans CSAE 31(11):103–109
Rana M, Mark T (2008) Mechanisms of salinity tolerance Annual. Rev Plant Biol 59:651–681
Ravindran KC, Venkatesan K, Balakrishnan V, Chellappan KP, Balasubramanian T (2007) Restoration of saline land by halophytes for indian soils. Soil Biol and Biochem 39(10):2661–2664
Rozema J, Schat RH (2013) Salt tolerance of halophytes, research questions reviewed in the perspective of saline agriculture. Environ Exp Bot 92:83–95
Safari S, Gunten K, Alam MS, Hubmann M, Blewett TA, Chi Z, Alessi DS (2019) Biochar colloids and their use in contaminants removal. Biochar 1(2):151–162
Saifullah, Dahlawi S, Naeem A, Rangel Z, Naidu R (2018) Biochar application for the remediation of salt-affected soils: challenges and opportunities. Sci Total Environ 625:320–335
Schmidt HP, Kammann C, Hagemann N, Leifeld J, Bucheli TD, Monedero M, Cayuela ML (2021) Biochar in agriculture—a systematic review of 26 global meta-analyses. GCB Bioenergy 13(11):1708–1730
Shaaban M, Van ZL, Bashir S, Younas A, Nunez-Delgado A, Chhajro MA, Kubar KA, Ali U, Rana MS, Mehmood MA (2018) A concise review of biochar application to agricultural soils to improve soil conditions and fight pollution. J Environ Manage 228:429–440
Shamsi NA, Hussain MI, El-Keblawy A (2020) Physiological responses of the xerohalophyte Suaeda vermiculata to salinity in its hyper-arid environment. Flora 273:151705
Sheng Y, Zhu L (2018) Biochar alters microbial community and carbon sequestration potential across different soil pH. Sci Total Environ 622–623:1391–1399
Shi J (2000) A case study of Minqin Oasis in China. Water Int 25:418–424
Shi Y (2003) Comprehensive reclamation of salt-affected soils in China's Huang-Huai-Hai Plain. J Crop Prod 7(1–2):163–179
Shih S, Myhre DL (1994) Ground-penetrating radar for salt-affected soil assessment. J Irrig Drain Eng 120(2):322–333
Shrivastava P, Kumar R (2015) Soil salinity: a serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation. Saudi J Biol Sci 22(2):123–131
Stephanie SL, Kurt TD, Mac D (2013) Yield and quality analyses of bioenergy crops grown on a regulatory brownfield. Biomass Bioenerg 49(2):123–130
Sun R, Zheng H, Yin S, Zhang X, You X, Wu H, Suo F, Han K, Cheng Y, Zhang C (2022) Comparative study of pyrochar and hydrochar on peanut seedling growth in a coastal salt-affected soil of Yellow River Delta China. Sci Total Environ 833:155183
Tang Y, Xie JS, Geng S (2010) Marginal land-based biomass energy production in China. J Integr Plant Bio 52(1):112–121
Tanji KK, Doneen LD, Ferry GV, Ayers RS (1972) Computer simulation analyses on reclamation of salt-affected soils in San-Joaquin Valley, California. SSSAJ 36(1):127–133. https://doi.org/10.2136/sssaj1972.03615995003600010030x
Tian et al (2021) World Soil Day| what about these "heavy tasting" plants that grow on saline-alkali soil? /s?id=1718289627997367022&wfr=spider&for=pc. https://baijiahao.baidu.com
Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314(5805):1598–1600
Wang MM, Zhou QX (2013) Environmental effects and their mechanisms of biochar applied to soils. Environ Chems 32(5):768–780
Wang Q, Wang B, Lee X, Lehmann J, Gao B (2018) Sorption and desorption of pb (II) to biochar as affected by oxidation and pH. Sci Total Environ 634:188–194
Wicke B, Smeets E, Dornburg V, Vashev B, Gaiser T, Turkenburg W, Faaij A (2011) The global technical and economic potential of bioenergy from salt-affected soils. Energy Environ Sci 4(8):2669
Wong V, Greene R, Dalal RC, Murphy BW (2010) Soil carbon dynamics in saline and sodic soils: a review. Soil Use Manage 26(1):2–11
Wu D, Senbayram M, Zang H, Ugurlar F, Aydemir S, Brüggemann N, Kuzyakov Y, Bol R, Blagodatskaya E (2018) Effect of biochar origin and soil pH on greenhouse gas emissions from sandy and clay soils. Appl Soil Ecol 129:121–127
Wu P, Ata-Ul-Karim ST, Singh BP, Wang H, Wu T, Liu C, Fang G, Zhou D, Wang Y, Chen W (2019) A scientometric review of biochar research in the past 20 years (1998–2018). Biochar 1(1):23–43
Xiao HY (2021) The characteristics of halophyte biochar and its application in improving red soil. Thesis, China Agricultural University, Beijing
Xiao HY, Lin QM, Li GT, Zhao XR, Li J, Li EZ (2022) Comparison of biochar properties from 5 kinds of halophyte produced by slow pyrolysis at 500°C. Biochar 4(1):12
Xu H, Cai AD, Wu D, Liang GP, Xiao J, Xu MG, Colinet G, Zhang WJ (2021) Effects of biochar application on crop productivity soil carbon sequestration and global warming potential controlled by biochar C: N ratio and soil pH: a global meta-analysis. Soil Tillage Res 213:105125
Yuan F, Leng BY, Wang BS (2016) Progress in studying salt secretion from the salt glands in recretohalophytes: how do plants secrete salt? Front Plant Sci 7:977

Yue Y (2017) The characteristics of biochar from halophyte plants and the amelioration effect and its mechanism on the salt-affected soil. Thesis, China Agricultural University, Beijing
Yue Y, Guo WN, Lin QM, Li GT, Zhao XR (2016) Improving salt leaching in a simulated saline soil column by three biochars derived from rice straw (*Oryza sativa* L) sunflower straw (*Helianthus annuus*) and cow manure. J Soil Water Conserv 71(6):467–475
Yue Y, Lin QM, Irfan M, Chen Q, Zhao XR (2016) Characteristics and potential values of bio-oil, syngas and biochar derived from Salsola collina Pall. In a fixed bed slow pyrolysis system. Bioresour Technol 220:378–383
Zhang J (2014) Coastal saline soil rehabilitation and utilization based on forestry approaches in China. Springer, Berlin Heidelberg, pp 9–13
Zhou ZD, Gao T, Van ZL, Zhu Q, Yan TT, Xue JH, Wu YB (2019) Soil microbial community structure shifts induced by biochar and biochar-based fertilizer amendment to karst calcareous soil. Soil Sci Soc Am J 83(2):398–408
Zhou ZD, Gao T, Zhu Q, Yan TT, Li DC, Xue JH, Wu YB (2019) Increases in bacterial community network complexity induced by biochar-based fertilizer amendments to karst calcareous soil. Geoderma 337:691–700
Zhu X, Chen B, Zhu L, Xing B (2017) Effects and mechanisms of biochar-microbe interactions in soil improvement and pollution remediation: a review. Environ Pollut 227:98–115