Review Article | Open Access

Zaib et al., 2022. 24 (3&4): 29-36. J. Environ. Agric. Sci. (ISSN: 2313-8629)

Remediation of Saline Soils by Application of Biochar: A Review

Muhammad Zaib [1,*], Usama Farooq [1], Muhammad Adnan [1], Saleem Sajjad [1], Zaheer Abbas [1], Kamran Haider [1], Noreen Khan [1], Roaid Abbas [1], Awon Shahzeb Nasir [2], Muhammad Furqan Muhay-Ul-Din [3]

Edited by:
Fahd Rasul,
University of Agriculture, Faisalabad, Pakistan

Reviewed by:
Qaiser Hussain,
PMAS Arid Agriculture University, Rawalpindi, Pakistan

Hasnain Farooq
University of California, Riverside, United States of America

Received
August 25, 2022
Accepted
November 18, 2022
Published Online
December 28, 2022

Abstract: Globally, agriculture is the backbone of farmers and plays a crucial role in food security, for a world with increasing population and food demand. As we know that the world's population is increasing rapidly every year, so the supply of food for the alarmingly increasing world population has become a serious problem. Food insecurity is aggravated by changing climatic conditions, soil degradation, and loss of arable lands due to various abiotic stresses, including salinity. Salinity greatly affects the world's agricultural lands due to various factors such as low availability of fresh and salt-free water, high temperature, etc. The salinity is caused by both primary and secondary processes. Primary salinity is mainly caused by many natural processes while secondary is mainly caused by human activities. Salinity is a land degradation process, characterized by a high concentration of soluble salts in the soil. It can suppress crop growth by influencing various functions and processes of plants, ultimately leading to significant yield reduction. Biochar is an organic-based material that helps to remediate soil salinity by various mechanisms in the soil system. Biochar has the potential to enrich microbial diversity and enhance activity which plays a vital role in the improvement of soil physical, chemical, and biological activities enhancing the productivity of the crops. The present review contains extensive details about salinity and its remediation using biochar.

Keywords: Biochar, carbon rich material, carbon sequestration, microbial activity, plant growth, salinity, soil salinity, sustainable agriculture.

***Corresponding author:** Muhammad Zaib email: zaibch767@gmail.com

Cite this article as Zaib, M., U. Farooq, M. Adnan1, S. Sajjad, Z. Abbas, K. Haider, N. Khan, R. Abbas, A.S. Nasir, M.F. Muhay-Ul-Din. 2022. **Remediation of Saline Soils by Application of Biochar: A Review**. Journal of Environmental & Agricultural Sciences. 24(3&4): 29-36.

1. Introduction

In the global landscape, agriculture dominates with around 4.7 billion hectares (i.e., 38% of the global land surface area) area under agriculture. Approximately one-third (around 1.6 billion hectares) is used for crop cultivation (FAO, 2022). Area under cultivation is rapidly decreasing due to urbanization, industrialization, soil degradation, climate change etc. (Winkler et al., 2021). Increasing food demand is mainly due to population increase, limited arable land, competition for resources, industrialization, market demand and other factors that led to an extensive prevalence of monoculture in agriculture (Calicioglu et al., 2019; Falcon et al., 2022).

Monocultures, dominate the global arable land and have resulted in various disadvantages, degradation of natural resources (e.g., soil), a buildup of diseases and

[1] Department of Soil and Environmental Sciences, University College of Agriculture, University of Sargodha, Sargodha, Punjab, Pakistan
[2] Department of Plant Breeding and Genetics, University College of Agriculture, University of Sargodha, Sargodha, Punjab, Pakistan
[3] Department of Agricultural Extension, University College of Agriculture, University of Sargodha, Sargodha, Punjab, Pakistan

pests, and productivity and crop yield decline. Moreover, Monocultures are major contributors to chemical contamination, deforestation, depletion of natural resources, loss of biodiversity, soil degradation, greenhouse gas emission (Bennetzen et al., 2016; Tubiello et al., 2022) vulnerability to climate change and overall global environmental changes (Bogužas et al., 2022; Bourke et al., 2021; de Groot et al., 2021). Recent estimates show that food production is responsible for up to 29% of global greenhouse gas emissions (Panchasara et al., 2021; Xu et al., 2021).

Increasing crop yields to meet increasing food demand is becoming a challenging task due to various abiotic stress (i.e., salinity, drought, heat, cold, etc.). It is important to reduce the effects of various stresses that affect crop productivity to meet increasing food demands (Falcon et al., 2022; Winkler et al., 2021).

2. Salinity

An increased concentration of salts, beyond a certain threshold, in both water and soil, is called salinity. It can cause water stress for the plants, which in turn affects their growth and development (Askari-Khorasgani et al., 2021; Eswar et al., 2021). Globally saline soils are a major challenge for agriculture, affecting crop yields and compromising the ability of farmers to grow crops in affected areas. Arid and semiarid areas are characterized by high temperatures, low precipitation and high evapotranspiration, salinity can be a major problem for crop production (Hassani et al., 2020; Hopmans et al., 2021).

2.1. Sources of Salinity

Salinity can accumulate in soils through a variety of mechanisms, including irrigation with saline water, the use of salt-based fertilizers, and natural processes such as weathering and erosion (Olson et al., 2022; Sabino et al., 2020). Salinity problems are divided into two categories, primary and secondary (Eswar et al., 2021). In primary salinity, various natural resources are responsible for the formation of saline soils such as parent materials from which salty soil is devolved, salt pans, salt lakes, salt precipitation, salt marshes and salt flats (Hopmans et al., 2021; Ondrasek and Rengel. 2021).

2.1.1. Natural Sources of Salinity

Changing climatic conditions have caused a remarkable increase in salinity (Rahman et al., 2018). Rising temperature and melting of glaciers have caused significant anomalies in the hydrological cycle and increased the water flow and altered the timings of water availability (Cunillera-Montcusí et al., 2022; Lassiter, 2021). Moreover, climate change has caused increased intensity, frequency and duration of extreme hydrological events (droughts, floods) (Tabari et al., 2021; Yang et al. 2021). These changes are causing seal level rise leading to salinity in coastal areas by altering the balance between saltwater and freshwater. Rising sea levels can shift the boundary between saltwater and freshwater upstream, causing seawater intrusion, imbalanced nutrient accumulation and freshwater salinization making it less suitable for human consumption or agriculture (Kaushal et al., 2021; Heiss et al., 2022).

2.1.2. Anthropogenic Activities and Salinity

Human activities have the greatest impact on the soil by reducing various soil properties and thereby altering the hydrological balance between different water uses. The process of soil degradation by human activities is called secondary salinization. Human activities play a major role in salinization (Mohanavelu et al., 2021). Ondrasek and Rengel. 2021). Land use-land cover change, such as urbanization, deforestation, and land clearing for agriculture can alter the natural water cycle, increases the rate of evaporation and lead to soil degradation and salinization of soil and water resources (Bhardwaj et al., 2019; Glatzle et al., 2020; Maertens et al., 2022; Yin et al., 2022). Irrigation with saline water can cause salt accumulation. If this practice continued for a longer period, it would aggravate the salinity issue. Moreover, inefficient drainage, over-irrigation and runoff from agricultural lands can also contribute to the salinity development of nearby water bodies (Zhao et al., 2020).

Industrial processes such as mining, and chemical manufacturing can release salts into the environment through wastewater discharge, or leaks (Cooper et al., 2022; Echchelh et al., 2018). Municipal wastewater discharge can contain high levels of salt, which can increase the salinity of water bodies and if used for irrigation purposes, it can deposit salts and other chemicals in agricultural soils (Bekir et al., 2022; Ezugbe et al., 2021; Ondrasek and Rengel. 2021). More than six percent of the world's land is affected by salinity.

Table 1. Remediation mechanisms of biochar in saline soils

Raw Materials	Addition rate of biochar	Treatment of salinity	Effects/ Mechanisms of biochar addition	References
Rice Husk	0, 50 gkg^{-1}	140.6 $meqL^{-1}$	i.Enhance Ca^{2+} and Mg^{2+} in soil solution. ii.Lower soil EC, ESP and SAR iii.Salt leaching	(Sadegh- Zadeh et al., 2018)
Sawdust	0, 5, 50 t/ha	30 gm^{-2}	i.Increase soil water availability ii.Transient Na^{+} binding	(Thomas et al., 2013)
Woodchip	75 t/ha	56.03 mM	i.Lower soil EC, ESP and SAR ii.Salt leaching	(Chaganti et al., 2015)
Conocarpus wood waste	0, 4, 8% w/w	7, 18.96 mM	i.Release mineral nutrients ii.Increase soil water availability	(Usman et al., 2016)
Hardwood, Softwood	0, 5 wt %	0, 25, 50 mM	i.Release mineral nutrients ii.Transient Na+ binding iii.Increase soil water availability	(Akhtar et al., 2015)

Of the world's 230 million hectares of arable irrigated land, 45 million hectares are currently affected by salinity and of the 1,500 million hectares under dryland agriculture; 32 million are salt-affected to changing amounts (FAO, 2022). The proportion of different countries in the world affected by salinity is shown in Table 1. Serious efforts are required to protect soil and aquatic resources from continued salinization (Hints et al., 2022; Schuler et al., 2019)

3. Effect of Salinity

3.1. Effects of Salinity on Soil

Under saline field environments, the nutrient interactions at the soil–plant level are complicated and regulated by several factors including soil water movements, accessibility of nutrients, structural stability of soil, humus content, organic matter, redox potential and pH in connection to the dissolution of salts in the rhizosphere (Rengasamy, 2016). Soil salinity can affect soil structure, reduce water holding capacity, disturb overall soil stability, and reduce soil organic content and water infiltration (Gonçalo et al. 2019). Salinity has various effects on soil, but increases in sodium absorption ratio (SAR), pH, exchangeable sodium percentage (ESP) as well as reductions in soil microbial activity and cation exchange capacity (CEC) indicate this condition of the soil (Roy and Chowdhury. 2020). Moreover, hyperosmotic stress in plants occurs when Na^{+} and Cl^{-} are high in plants and this condition leads to plant water deficit. Soluble salts can irritate plant roots by disrupting water absorption (Maathuis et al. 2014).

3.2. Effects of Salinity on Plants

Plants show various physiological, biochemical, molecular and morphological modifications in response to the increased salt concentrations in their environment (Meng et al. 2018). Salinity negatively influences almost all plant processes including plant growth and plant structure (Singh, 2022), through biochemical and physical disturbances, ionic imbalance and toxicity, nutrient deficiencies, and osmotic and oxidative stresses (Arif et al., 2020). These, salinity induced abnormalities, causes reduced nutrient and water uptake, and compromised photosynthetic efficiency leading to decreased crop yields are potential hazards associated with salinity (Naz et al., 2021; Yasir et al., 2021). Around 500 species (i.e., 0.14% of the global floristic diversity), can survive saline conditions (Isayenkov, 2019). Among these salt-tolerance species, few crops are also included, like quinoa, triticale, oats, wheat, barley and sorghum (Barros et al., 2021; Meng et al., 2018) (Table 2).

The presence of salts can affect plant reproduction and productivity due to the complex interactions between soil physico-chemical properties and plant morphological and physiological characteristics (Akbarimoghaddam et al. 2011). Salinity reduces soil water potential, hindering water and nutrient uptake. Plants collect salts together with the water they use and often accumulate Na^{+} and Cl^{-} ions in plant cells to toxic levels (Maathuis et al. 2014). Furthermore, cellular enzyme activity can be disrupted due to ionic imbalances, nutrient toxicity and water stress (Naz et al., 2021). These factors lead to different responses in plants, manifested by a variety of symptoms in cells and organs (Fig. 1).

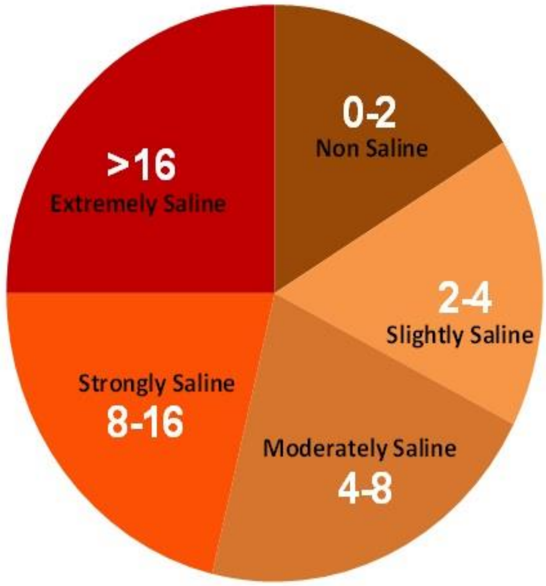

Fig. 1. Soil salinity classes based on EC (electrical conductivity) of the soil. Non-saline (EC 0-2 dSm^{-1}), slightly saline (EC 2-4 dSm^{-1}), moderately saline (EC 4-8 dSm^{-1}), strongly saline (EC 8-16 dSm^{-1}), extremely saline (EC >16 dSm^{-1}) (based on Richards 1954).

A reduction in respiration characterizes stressed plants, which also show an alteration in the distribution of assimilations, a process of inhibited photosynthesis and a weaker production of new leaves. At the same time, there are increased morphological changes in the organs (thickening and succulence of the leaves, reduced length of the internodes), wilting, drying and even necrosis of the organs and entire plants. In addition, growing crops in saline areas can be detrimental to their appetite (Kumar and Verma, 2018). Rogers (1997) tested the

The impact of salinity on plants can be classified in three categories: first of all, salts impair water absorption from the soil, exposing plants to water stress which can result in retarded growth and decreased yield. Secondly, excessive absorption of certain salt ions like Na+ and CI- can cause toxicity in plants and consequently damaging to the internal structures of plants, affecting physiological processes and frequently reducing plant growth, leaf burn, or even plant demise. Thirdly, imbalanced ions due to increased uptake of salt ions might inhibit the availability of other key nutrients (e.g. potassium, magnesium, nitrogen, phosphorus). Thus, salt influence on plant growth through various systems, increasing the soil osmotic stress, hyperaccumulating certain ions in plant tissue, and changing the plant nutrient dynamics (Askari-Khorasgani et al., 2021; Tanu, 2022).

3.3. Effect of Salinity on Microorganisms

Soil salinity is a major problem which can reduce soil microbial community, enzymatic activity, respiration rate of soil, and the bacteria growth of the soils (Naz et al., 2021; Tripathi et al. 2006). Osmotic and specific ion effects are the two basic processes of soluble salts that can affect soil microbes. Soluble salts enhance the osmotic capacity of soil water, which pull out water from the cells. Osmotic effect and specific ion effect are the two basic processes of soluble salts that can affect soil microbes. Earth osmotic potential increases due to soluble salts. Leaking water from the cell causes the cell to shrink and can kill microbes to get water out of the soil. If the osmotic potential is low, then that condition can also make difficult to the plant roots and microbes to get water from the soil (Grossiord et al., 2020).

Microorganisms play a vital role in plant productivity, soil structure and various function of soil. Microbes of soil comprise bacteria, fungi, archaea, viruses and protozoa (Mahmood et al., 2021). Microorganisms participate in ammonification, oxidation, nitrification, nitrogen fixation and other activities which lead organic matter to decompose and deliver nutrients to plants to maintain their life cycle (Zhang et al., 2019). Microorganisms can also accumulate carbon and other nutrients in their biomass which are converted into inorganic material which can enhance soil fertility after cell death by living microbes (Yan et al., 2015).

Excessive salt concentrations can affect the structure and composition of soil microbiota (Liang et al., 2022). Since the salt-affected soils have low osmotic potential, different microbial genotypes can survive on low osmotic potential. Most of these die at low osmotic potential (Llamas et al. 2008). Fungi is more susceptible to osmotic stress than bacteria (Mandeel, 2006). Salt stress has a negative impact on soil microbial community (Mahmood et al., 2021; Zhang et al., 2019).

Soil microorganism plays a vital role in the regulation of ecosystem functions (Singh and Gupta, 2018). Microbial biodiversity in saline soils is most affected by other factors such as pH and nutrient availability (Lozupone and Knight, 2007). Respiration is frequently used to measure the microbial activity in the soil (Yan and Marschner, 2013), according to the rate of degradation of organic matter, an increase in the rate of respiration in the soil causes stress (Mamilov and Dilly, 2002).

Table 2. Effects of biochar on plants grown under saline conditions

Salt Status growth medium	Characteristics of Biochar				Test crop/parameter	Rate of Biochar Application	Response (%)	Reference
	Raw Material	pH	CEC (cMc kg⁻¹)	Ca (%)				
30 g NaCl m^{-2}	*Fagus grandifolia* sawdust, 378 °C	6.18	16.2	0.29	Indian mallow (*Abutilon theophrasti* L.)/plant survival till 60 days Common Self-heal (*Prunella vulgaris*	1. 5 t ha^{-1} 2. 50 t ha^{-1}	1. a. ns, b. +52 2. a. +100, b. +49 1. a. ns, b. ns 2. a. +30, b. ns	Thomas et al., 2013
$EC_{1:5}$ 1.3 dS m^{-1} ESP 80	Rice hull	10.2	50		Maize (*Zea mays* L.)/dry matter	5% w/w	+ 120	Kim et al., 2016
$EC_{1:5}$ 1.3 dS m^{-1}	Coniferous wood chip, 500 °C				Garden lettuce (*Lactuca sativa* L.)/shoot dry matter			Hammer et al., 2015
Salts 1.5% $pH_{1:2.5}$ 9.0	Corn stalks, 400 °C	9.6			Wheat (*Triticum Aestivum* L.)/grain yield Soya bean (*Glycine max* L.) / grain yield	1. 1.5 t ha^{-1} 2. 5 t ha^{-1} 3. 10 t ha^{-1}	0.08	Lin et al. (2015)
ESP 59 EC 1.0	Peanut shell biochar Compost, 350 °C	8.4			Sesbania (*Sesbania grandiflora* L.)/shoot biomass	1. 1.5 t ha−1 2. 5 t ha−1 3. 10 t ha−1	1. + 341 2. + 148 3. −59	Luo et al., 2017
$EC_{1:5}$ 239 dS m^{-1} pH 8.59	Wheat straw, 300 °C	693	18.8		Suaeda salsa (*Chenopodina salsa* L.)/shoot biomass	1. 5% w/w 2. 10% w/w 3. 20% w/w	1. + 11 2. + 121 3. + 110	Sun et al. (2017)
25 mM NaCl water irrigation 50 mM NaCl water irrigation					Potato (*Solanum tuberosum*)/tuber yield	+43		Akhtar et al., 2015)

3.4. Effect of Salinity on Humans Health

Salinization of land and water has been increasing over the last few years due to rising sea levels (Hassani, et al., 2020; Lassiter, 2021; Singh, 2022). Salinity has become a major problem for people living in coastal areas (Rahman et al., 2018; Tanu, 2022). Increasing salinization of water cause problems such as lack of drinkable water, irrigation, agricultural problems, high blood pressure, and kidney malfunctions by increased salt consumption through drinking saline water (Kaushal et al., 2021). Therefore, they are at higher risk of high blood pressure and many other diseases than people who live in cities (Rasheed et al. 2014). According to the WHO, many people in coastal regions take more sodium than the desirable daily intake (>5 g/day) (Rasheed et al. 2014). There is a strong relationship between blood pressure and Na (Aburto et al. 2013). One-third of the world's deaths and three-quarters in economically weaker countries are associated with cardiovascular diseases, mainly due to increased consumption of soluble salts (World Health Organization, 2015). Higher salt concentrations in the groundwater also significantly negative impact on human health. People living in coastal areas have money to spend, but there are no fresh fruits or vegetables in the markets. As a result, coastal communities are forced to eat locally grown food, with high salt concentrations (Rasheed et al. 2014).

4. Soil Amendments

A variety of organic and inorganic amendments can be used to maintain or improve soil productivity. Organic amendments are known to provide macro and micronutrients that are essential for plant growth. Animal manure, crop rotation and plant residues are essential to maintain soil fertility and this phenomenon can support the soil to provide various nutrients (Khan et al., 2022). These organic amendments can provide long-term soil N, especially at the rate of mineralization of the organic matter incorporated. Both macro and micronutrient content are highly dependent on the organic sources and quality of organic amendments (Quilty and Cattle, 2011).

However, due to world population growth, necessary to meet increasing global food requirements, many organic amendments have been replaced by inorganic fertilizers, which are more expensive than organic amendments. Synthesized fertilizer helps plants store their own nutrients, also helping plants obtain the nutrients they need from the soil. Organic amendments can be easily adopted on a small scale (Jensen et al. 2011). However, excessive application of fertilizers leads to soil degradation, can also affect biodiversity and is also detrimental to the environment. However, mostly, when various chemicals such as nitrate, potassium and phosphate etc. can cause groundwater contamination, which is harmful to humans (Mohanavelu et al., 2021).

4.1. Biochar and Soil Characteristics

Biochar is a major source of carbon, derived from the burning of plant-based materials at high temperatures in the absence or little presence of oxygen. Application of biochar in soils has become an important source to provide carbon-rich material. Since biochar is a major source of important nutrients that are essential for plant growth and soil structure, biochar has been used as a soil amendment to increase soil fertility for the past few decades (Guo et al. 2020). Utilization of biochar under various abiotic stresses is a beneficial and important source of nutrients to enhance fertility and maintain various morphological processes of plants (Kim et al. 2016). The physicochemical properties of the soil have also been upgraded using biochar (Niazi et al. 2016).

Biochar is obtained by pyrolysis, in the absence or low presence of oxygen, of plant or animal-based materials at a high temperature of 300-600℃. Once incorporated into the soil, this material increases soil carbon storage as the material is thermally transformed (Sakhiya et al. 2021). An internal structure like graphite biochar is considered a high-quality biochar that can store carbon in soil over thousands of years (Sakhiya et al. 2021). Biochar is applied to soil as a soil conditioner because it can be used as a plant life promoter in the soil (Lehmann et al 2011). Field experiments with biochar application in soil have benefited agricultural productivity.

4.2. Biochar-based Materials

There is a growing interest in the application of biochar for soil amendments, soil fertility enrichment and carbon sequestration (Haider et al., 2022; Karim et al., 2022; Saifullah et al., 2018). Biochar is a plant-based material that comes into existence by the burning of different plants-based materials at a high temperature in the presence or little existence of oxygen. In the past, researchers have done a lot of work on increasing the efficiency of biochar, and these efforts are currently ongoing. This review will focus on different types of biochar that remove pollutants from soil and water. There are various materials that are used to enhance the performance of biochar such as compounding, doping and chemical activation of the material. Biochar is produced from plant-based materials like wood, grasses, crop residues etc. at a high temperature by the process of pyrolysis. There are various sources of biochar such as animal manure, twigs, fruit pits, crop straw and residues, forestry waste and some bag and food waste (Parthasarathy et al., 2022; Rahman et al., 2020; Sigua et al., 2014).

Biochar is produced by biomass and is a low-cost product used in arable lands to improve soil physiochemical properties of soils (Qiu et al., 2021; Shakoor et al., 2021). Different organic materials made biomass such as agricultural residue, forest residues, sludge, and food waste. This waste material is readily available all over the world and is found everywhere (Akhil et al., 2021; Marti et al., 2021). Disposal of this type of bio-waste is a problem, so converting this type of waste into biochar is a viable strategy. Two methods of biochar production are hydrothermal and pyrolysis. The pyrolysis method is mainly used in the production of biochar. The quality of biochar depends on the properties of biomass used for biochar preparation (Premarathna et al., 2019).

Mostly biochar is produced from plant-based materials which are cheaper, easily available and nutrient-rich (Singh et al., 2015). Millions of tons of residual waste are generated every year due to the influence of human activities. Low-cost biochar is produced due to the presence of large amounts of cellulose and lignin in biomass. Biochar can decrease pollutants through the porous structure of biochar (Haider et al., 2022).

Salt-infested soils often suffer from malnutrition and low use of organic compounds. As a result, this problem can decrease crop yield (Mahmoud et al. 2019). The presence of phosphorus in salt-affected soils has reduced the productivity of fields (This reduction in plant yield is due to the precipitation of phosphorus with Ca ions) (Penn and Camberato, 2019). So, the presence of P in saline fields and how to maintain it is a serious problem today. Most of the arid and semi-arid regions of the world are highly affected by mineral salts and these salts are also known as plant stress (Most of the hot regions of the world are more affected by salinity due to less rainfall and less water availability for leaching of salts from the root zone). A report estimated that more than 7% of the world's land or 1.1 Gha is highly affected by salinity (Wicke et al. 2011).

Salinity causes various soil disturbances such as uptake of nutrients, membrane permeability and water absorption. Salinity causes various changes in plant metabolism and nutrient balance, hormonal balance, production of reactive oxygen species (ROS) and gas exchange (Munns, 2002). This salinity-induced soil disturbance causes various changes in cell growth and cell division, plant reproduction and plant growth, resulting in plant death (Rezaei and Razzaghi, 2018). Salinity affects the internal processes of various plants as well as the external structure. Salinity disrupts plant processes such as seed germination, nutrient availability, water retention and nutrient uptake, eventually leading to plant death (Ali et al. 2017).

The application of biochar in saline soils improved the physicochemical properties and soil structure of the soil, the application of amendments also improved the organic content and nutritional status of the degraded soil by salinity, also increasing cation exchange capacity (CEC) by supplying Ca to the soil solution and displacing Na from exchange sites (Mohanavelu et al., 2021). Therefore, biochar improves soil physical properties to enhance water-holding capacity and maintain soil porosity. Moreover, in saline soils biochar improves activities of soil microorganisms to recover saline soils (Amini et al. 2016). Application of this material in salt-affected soils accelerates the leaching process and thereby this material thus reduces the time required to reclaim salt-affected soils and alleviate the negative impact of salinity on crop production (Yue et al. 2016).

Addition of biochar in the soil increases the stability of organic molecules and improves organic carbon which will support attached soil aggregates with each other for longer periods than other organic amendments with easily degradable molecules (Wu et al., 2017). Moreover, studies have shown that the addition of biochar as an organic amendment to saline soils helps to improve the physiochemical properties of saline soils (Zhang et al. 2019) and biological (Zheng et al. 2022) soil properties are interrelated to each other to remove sodium-like as electrical conductivity (EC), sodium leaching and sodium adsorption ratio (Saifullah et al. 2018). Application of biochar to saline soils in potato fields can reduce salt stress on crops (Mohanavelu et al. 2021). Biochar use in saline soils is more reliable as it can absorb more salts (Na^{+}) (Saifullah et al., 2018).

4.3. Impact of Biochar on Soil EC

Massive amounts of water are required for washing out salts from the rhizosphere. A high volume of water used for irrigation avoids the accumulation of salts in the root zone (Mohanavelu et al., 2021). The rate of leaching of soluble salts from salt-affected soils can be enhanced by various organic and inorganic amendments (Palansooriya et al., 2019). Many reports have suggested that biochar application can facilitate salt leaching from salt-affected soils and reduce soil EC (Yue et al., 2016; Lashari et al., 2015). It was reported that the application of biochar in different trials decrease the EC of salt-affected soils. A decrease in EC accelerates the leaching of salts and improves soil hydraulic conductivity and porosity of soil (Yue et al., 2016). Application of amendments in salt-affected soils maintains soil physicochemical properties. Hence, the use of different amendments in salt-affected soils facilitates the leaching of soluble salts. It was reported that EC was reduced by 42% using both poultry manure and biochar (Lashari et al., 2015).

Modification in the EC of salt-affected soils depends entirely on the aging, amount and types of biochar. In some cases, application of biochar can increase the EC of salt-affected soils if the EC of applied biochar is higher than salt-affected soils. Moreover, the EC of water used for irrigation is also important. If irrigation water has a higher EC, it will lead to the accumulation of salts rather than salt leaching (Yue et al., 2016). Contrarily, the application of biochar with EC lower than the soil EC will facilitate the leaching of salts from the rhizosphere (Mohanavelu et al., 2021).

4.4. Impact of Biochar on Soil pH, SAR

Biochar is an amendment used to improve soil structure. It has been reported in many experiments and there is a large amount of data available on increasing the pH of salt-stressed soils with the application of biochar (Nath et al., 2022). Most of the experiments have been conducted in soils with low pH using biochar (Liu et al., 2017), also reported that in high pH soils, the results of using low pH biochar would be just the opposite (Liu et al., 2017). While various previous studies have shown that applying biochar to saline soils reduces the pH of saline-affected soils (Wu et al., 2017) the mechanisms for lowering pH are unclear. It is due to the exchangeable sodium percentage (ESP) associated with saline-sodic and high pH of sodic soils. Application of biochar in saline soils reduces the ESP of salt-affected soils, which is responsible for pH reduction (Lashari et al., 2015). Moreover, the initial pH of applied biochar is very helpful for the pH of salt-affected soils pH and this initial pH of biochar is very useful in various changes that occur by the application of biochar in salt-affected soils. It has been observed that soil pH and ESP can be modified by the application of different types of biochar in salt-affected land (Sun et al. 2016) (Table 2). Also, in salt-affected soils (pH 8.4) a measurable change in pH has been observed with biochar (low pH 3.1) application. Therefore, the main reason for the change in the pH of the affected soil is the difference between the pH of the salt-affected soil and the pH of the applied biochar (Murtaza et al., 2021; Nath et al., 2022).

On the other hand, many previous studies show the beneficial effects of biochar on soil sodium absorption ratio (SAR) and exchangeable sodium percentage (ESP). Several trials reported that the application of biochar under salt conditions can reduce the SAR/ESP of affected soils (Sun et al., 2017). The interaction of Ca and Na in soil depends on the value of SAR and the type of biochar that can increase the content of Na and Ca. The effect of biochar on SAR is controlled by the rate and type of biochar (Kim et al., 2016). High levels of Na-containing biochar can increase SAR or ESP of salt-affected soils (Zheng et al., 2022). Consequently, before the incorporation of biochar in salt-affected soils it is recommended that the pre-testing process for Na content (Murtaza et al., 2021).

4.5. Influence of Biochar on Soil Nutrient Pool

Due to chemical, physical and biological degradation of salt-affected soils, such soils suffer from nutrient deficiency, imbalanced nutrient status, and ion toxicity (Arif et al., 2020). High concentrations of Na in salt-affected soils can reduce uptake of essential nutrients by plant roots (Maathuis et al. 2014). Salt-affected soils are generally low in organic matter from plant biomass and sodium, phosphorus and potassium for various reasons (Rengasamy, 2016).

Application of soil nutrients under salt stress conditions can improve crop productivity (Olson et al., 2022; Sabino et al., 2020). As biochar is produced by burning plant-based materials, it contains various plant nutrients that are applied to soil after being deposited in salt-affected soil (Ali et al., 2017; Amini et al., 2016). Thus, the application of biochar in salt-affected soils can increase nutrient status and meet plant nutrient requirements (Karim et al., 2022). Phosphorus (P) is an essential macronutrient and a limiting nutrient for plants (Ros et al., 2020). In soil, P supply is pH dependent, its availability is maximum near pH 6.5. As pH increases it resulted in higher P-fixation by calcium, whereas lower pH causes p-fixation aluminum. As salt-affected soils have higher pH levels and lower organic matter content than optimal soils, high pH limits plant growth due to low availability of P (Penn and Camberato, 2019).

Biochar is used as a source of P and soil organic carbon in salt-affected soils. Therefore, application of biochar in the saline environment increased the availability of P nutrients for the growth of plants (Glaser and Lehr. 2019; Lashari et al., 2013), or can rise the growth of P-solubilizing bacteria in the rhizosphere (Liu et al., 2017). Carbon-rich materials are the result of the decomposition of plant and animal materials under aerobic or anaerobic conditions and are used as a nutrient supplement that enhances soil properties (Mohanavelu et al., 2021). Biochar effects directly soil physical, chemical, and microbial diversity (Sun et al. 2017; Rizwan et al. 2016). Biochar has significant potential to convert hydrogen ions, and the capability to interchange anions or cations, and it is considered a profitable, biologically accessible, and efficient adaptive absorber (Huang et al. 2020). It is a soil modifier and can be used to bind contamination; it can also use to enhance microbes in the fields (Mohan et al., 2014).

Long-term management efforts are required to ameliorate salt-affected soils; hence, transitional or temporary policies to manage salinity can be a suitable possibility to enhance field returns. There are several benefits to using Biochar in small amounts in water (Sun et al. 2017). Since salt stress is known to suppress the productivity of arable lands, we can increase tolerance in plants by using biochar (Fig. 1). Biochar is used as a soil amendment to increase soil fertility. Table 1 summarizes the valuable effects of biochar.

The use of biochar is beneficial in salt-affected soils, which significantly improves the chemical and physical properties of soil by reducing the effect of salts on plants through the release of sodium (Sun et al. 2017). Biochar can improve soil properties in salinity, water retention, drought and temperature stress (Rizwan et al. 2016). reported that the application of poultry manure biochar in maize crop can increase microbial biomass C in saline soils and increase the activity of enzymes that produce ammonia and CO2 from urea and can also increase invertase enzymes activity in the formation of fructose and glucose (Bhaduri et al., 2016).

The properties of salt-affected soils can also be enhanced with the use of carbon-based amendments (Mohanavelu et al., 2021; Zheng et al., 2022). Though, there is little record of the effects of biochar in salt-affected soils. Soil pH can't be disturbed by the addition of biochar 30 g/m^2. However, the use of biochar increases the EC of salt-affected soils as compared to low (Zhang et al., 2019; Zheng et al., 2022). Also, furfural biochar in salt-affected soils reduced H^+ ions, while increasing the soil organic carbon and cations exchange capacity and accessible phosphorous in the soil (Wu et al. 2017). Furthermore, the current details show that biochar is rich in calcium and magnesium ions and also can improve their accessibility when introduce into the soil as substances that can increase soil properties and ameliorate soil health (Rajkovich et al. 2012). Aggregation of soil particles and soil structure can be improved with the application of biochar, which will increase soil water and nutrient holding capacities, reducing water and nutrient losses (O'Connor et al. 2008).

Application of carbon-rich black material with a pyroligneous solution can reduce pH level, sodium and sodium chloride content in salt-affected soils. Biochar supplementation can also increase soil organic carbon and phosphorus content in salt-affected soils. Biochar can be used to reduce the effects of soluble salts (salinity) or exchangeable sodium (sodicity) through the adsorption of sodium ions (Lashari et al., 2013). In potatoes grown under salinity stress, biochar application can reduce salinity stress with the help of high Na^+ adsorption capacity of biochar materials (Saifullah et al., 2018; Lashari et al., 2014). Biochar can stimulate microbial activity, as it is a source of carbon for microbial activity, and it is more degradable. It can support small amounts of soil microbes. However, the release of short-term labile pyrolysis products can stimulate topsoil organic activity (Lehman et al. 2011).

Biochar is a good carbon source used for carbon enrichment or carbon storage. Another viable purpose is to supply a rich source of carbon in the soil for living organisms for the significant enhancement in microbial activity in saline fields after the incorporation of biochar. Earlier statements on the effects of carbon-rich material on soil microbes carbon are inconsistent. In certain trials, amendment with carbon-rich material had no significant impact whereas the introduction of carbon-rich material (biochar) remarkably can reduce microbe's carbon (Palansooriya et al., 2019; Zheng et al., 2022).

Carbon-rich biochar has significant impacts on soil microbes. Even microbial biomass carbon reproduces some variations in soil organic material and decay. Therefore, any methods and resources that enhance or reduce soil carbon material can disturb biomass and MCA. Therefore, biochar is a resource of carbon that can store extra carbon for soil microbes and enhance the total carbon of soil microbial activity (Zhang et al. 2019).

4.6. Role of Biochar in Carbon Sequestration and Climate Change Mitigation

Emissions of greenhouse gases from various human activities have increased over the past few decades. Production and application of carbon-rich materials in soil have achieved great significance (Hong et al., 2021; Woolf et al. 2010). Biochar is a highly porous material with significant carbon sequestration potential, also for long periods of time. These properties make it a potential tool for climate change mitigation (Gross et al., 2021; Lehmann et al. 2006; Xu et al., 2021)

The carbon sequestration potential of biochar depends on the type of material used for its production, production process involved, and the soil conditions where it is applied. Improved soil fertility, water retention, and enhanced plant nutrient uptake through biochar application can reduce dependence on synthetic fertilizers, and thereby reduce the emission of greenhouse gases (Khadem et al., 2021; Sarfraz et al., 2019; Zhang et al., 2019).

4.7. Impact of Biochar on Microbial Community

High-stability of biochar is key for its prolonged retention and delayed decomposition in the soil through the activity of soil microorganisms (Wu et al. 2017). These soil microbes play an important role in the soil such as nutrient cycling, and fixation, P-solubilization, etc. Soil microbes perform important ecological services including recycling different fractions of organic waste. These microbes play an important role in the process of mineralization, immobilization, etc. The community and diversity of soil microorganisms have a significant impact on soil quality, structure, soil health, soil productivity, soil fertility, and ecosystem function (Khadem et al., 2021; Zou et al. 2017). Biochar has a direct effect on the soil microbial community. It can increase the diversity, number, and activity of soil microbiota in carbon-rich soils (Liu et al., 2017; Zhang et al. 2019). Scientists are interested to enhance the properties of biochar which are essential for soil health (Sun et al. 2017; Rizwan et al. 2016).

5. Conclusion

Salinity is the most emerging problem all over the world. Soil salinity has various negative effects on performance and productivity. Various inorganic and organic amendments are used to treat salt-affected soils. Biochar is a promising choice for soil reclamation, its application to soil can improve the properties of saline soils and promotes plant growth. This method is inexpensive and can be easily adapted on both small and large scales. Biochar is a rich source of nutrients, essential for the proper growth of plants, maintaining the photosynthesis process, improving nutrient uptake and reducing sodium uptake. Biochar, a carbon-rich material, enhances the microbial community in saline soils. More studies are required to evaluate the role of biochar under both drought and salt stress conditions. Soil salinity can be reduced by avoiding over-irrigation, using good quality water for irrigation and mulching the soil to maintain soil temperature which helps soils retain water for longer periods and reduce evaporation rates.

Competing Interest Statement: None of the authors have any competing interests.

List of Abbreviations: EC, Electrical conductivity; SAR: Sodium Adsorption Ratio

Acknowledgment: Authors would like to thank Dr. M. Imtiaz, Soil and Environmental Biotechnology Division, National Institute for Biotechnology and Genetic Engineering (NIBGE), Faisalabad, Punjab, Pakistan, for his help in writing and reviewing the manuscript, and moral support to complete this manuscript.

References

Aburto, N.J., A. Ziolkovska, L. Hooper, P. Elliott, F.P. Cappuccio and J.J. Meerpohl. 2013. Effect of lower sodium intake on health: systematic review and meta-analyses. British Med. J. 346:1–20.

Akbarimoghaddam, H., M. Galavi, A. Ghanbari and N. Panjehkeh. 2011. Salinity effects on seed germination and seedling growth of bread wheat cultivars. Trakia J. Sci. 9(1):43–50.

Akhil, D., D. Lakshmi, A. Kartik, D.-V. N. Vo, J. Arun and K. P. Gopinath. 2021. Production, characterization, activation and environmental applications of engineered biochar: a review. Environ. Chem. Lett. 19: 2261-2297.

Akhtar S.S., M.N. Andersen and F. Liu. 2015. Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress, Agri. Water Manag. 158: 61-68.

Ali, S., M. Rizwan, M.F. Qayyum, Y.S. Ok, M. Ibrahim, M. Riaz, M.S. Arif, F. Hafeez, M.A. Wabel and A.N Shahzad. 2017. Biochar soil amendment on alleviation of drought and salt stress in plants: A critical review. Environ. Sci. Pollut. 24:12700-12712.

Amini, S., H. Ghadiri, C. Chen and P. Marschner. 2016 Salt-affected soils, reclamation, carbon dynamics, and biochar: A review. J. Soils Sediments. 16:939-953.

Arif, Y., P. Singh, H. Siddiqui, A. Bajguz and S. Hayat. 2020. Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. Plant Physiol. Biochem. 156: 64-77.

Askari-Khorasgani, O., M. I. A. Rehmani, S. H. Wani and A. Kumar. 2021. Osmotic stress: an outcome of drought and salinity *Handbook of Plant and Crop Physiology. pp.* 445-464. CRC Press.

Barros, N. L. F., D. N. Marques, L. B. A. Tadaiesky and C. R. B. de Souza. 2021. Halophytes and other molecular strategies for the generation of salt-tolerant crops. Plant Physiol. Biochem. 162: 581-591.

Bekir, S., R. I. Zoghlami, K. Boudabbous, M. N. Khelil, M. Moussa, R. Ghrib, O. Nahdi, E. Trabelsi and H. Bousnina. 2022. Soil Physicochemical Changes as Modulated by Treated Wastewater after Medium-and Long-Term Irrigations: A Case Study from Tunisia. Agriculture. 12: 2139.

Bennetzen, E. H., P. Smith and J. R. Porter. 2016. Agricultural production and greenhouse gas emissions from world regions—The major trends over 40 years. Glob. Environ. Chang. 37: 43-55.

Bhaduri, D., A. Saha, D. Desai and H.N. Meena. 2016. Restoration of carbon and microbial activity in saltinduced soil by application of peanut shell biochar during short-term incubation study. Chemosphere. 148:86–98.

Bhardwaj, A. K., V. K. Mishra, A. K. Singh, S. Arora, S. Srivastava, Y. P. Singh and D. K. Sharma. 2019. Soil salinity and land use-land cover interactions with soil carbon in a salt-affected irrigation canal command of Indo-Gangetic plain. CATENA. 180: 392-400.

Bogužas, V., L. Skinulienė, L. M. Butkevičienė, V. Steponavičienė, E. Petrauskas and N. Maršalkienė. 2022. The Effect of Monoculture, Crop Rotation Combinations, and Continuous Bare Fallow on Soil CO2 Emissions, Earthworms, and Productivity of Winter Rye after a 50-Year Period. Plants 11, 431.

Bourke, P. M., J. B. Evers, P. Bijma, D. F. van Apeldoorn, M. J. M. Smulders, T. W. Kuyper, L. Mommer and G. Bonnema. 2021. Breeding Beyond Monoculture: Putting the "Intercrop" Into Crops. Front. Plant Sci. 12:734167.

Calicioglu, O., A. Flammini, S. Bracco, L. Bellù and R. Sims. 2019. The Future Challenges of Food and Agriculture: An Integrated Analysis of Trends and Solutions. Sustainability. 11: 222.

Cooper, C. M., J. McCall, S. C. Stokes, C. McKay, M. J. Bentley, J. S. Rosenblum, T. A. Blewett, Z. Huang, A. Miara, M. Talmadge, et al. 2022. Oil and gas produced water reuse: opportunities, treatment needs, and challenges. ACS ES&T Eng. 2: 347-366.

Cunillera-Montcusí, D., M. Beklioğlu, M. Cañedo-Argüelles, E. Jeppesen, R. Ptacnik, C. A. Amorim, S. E. Arnott, S. A. Berger, S. Brucet, H. A. Dugan et al. 2022. Freshwater salinisation: a research agenda for a saltier world. Trend. Ecol. Evol. 37: 440-453.

de Groot, G. S., M. A. Aizen, A. Sáez and C. L. Morales. 2021. Large-scale monoculture reduces honey yield: The case of soybean expansion in Argentina. Agric. Ecosyst. Environ. 306:, 107203.

Echchelh, A., T. Hess and R. Sakrabani. 2018. Reusing oil and gas produced water for irrigation of food crops in drylands. Agric. Water Manag. 206: 124-134.

Eswar, D., R. Karuppusamy and S. Chellamuthu. 2021. Drivers of soil salinity and their correlation with climate change. Curr. Opin. Environ. Sustain. 50: 310-318.

Ezugbe, E. O., E. Kweinor Tetteh, S. Rathilal, D. Asante-Sackey and G. Amo-Duodu. 2021. Desalination of municipal wastewater using forward osmosis. Membranes. 11: 119.

Falcon, W. P., R. L. Naylor and N. D. Shankar. 2022. Rethinking Global Food Demand for 2050. Popul. Devel. Rev. 48: 921-957.

FAO. 2022. Land use statistics and indicators. Global, regional and country trends, 2000–2020. FAOSTAT Analytical Brief, no. 48. Rome. https://doi.org/10.4060/cc0963en

Glaser, B. and V.-I. Lehr. 2019. Biochar effects on phosphorus availability in agricultural soils: A meta-analysis. Sci. Rep. 9: 9338.

Glatzle, A., L. Reimer, J. Núñez-Cobo, A. Smeenk, K. Musálem and R. Laino. 2020. Groundwater dynamics, land cover and salinization in the dry Chaco in Paraguay. Ecohydrol. Hydrobiol. 20: 175-182.

Gonçalo Filho, F., N. da Silva Dias, S. R. P. Suddarth, J. F. S. Ferreira, R. G. Anderson, C. dos Santos Fernandes, R. B. de Lira, M. F. Neto and C. R. Cosme. 2020. Reclaiming tropical saline-sodic soils with gypsum and cow manure. Water. 12: 57.

Gross, A., T. Bromm and B. Glaser. 2021. Soil organic carbon sequestration after biochar application: A Global Meta-analysis. Agronomy. 11: 2474.

Grossiord, C., T. N. Buckley, L. A. Cernusak, K. A. Novick, B. Poulter, R. T. W. Siegwolf, J. S. Sperry and N. G. McDowell. 2020. Plant responses to rising vapor pressure deficit. New Phytol. 226: 1550-1566.

Guo, X., H. Liu, and J. Zhang. 2020. The role of biochar in organic waste composting and soil improvement: A review. Waste Manag. 102: 884–899.

Haider, F. U., A. L. Virk, M. I. A. Rehmani, M. Skalicky, S. T. Ata-ul-Karim, N. Ahmad, W. Soufan, M. Brestic, A. E. L. Sabagh and C. Liqun. 2022. Integrated Application of Thiourea and Biochar Improves Maize Growth, Antioxidant Activity and Reduces Cadmium Bioavailability in Cadmium-Contaminated Soil. Front. Plant Sci. 12: 809322.

Hammer, E. C., M. Forstreuter, M. C. Rillig and J. Kohler. 2015. Biochar increases arbuscular mycorrhizal plant growth enhancement and ameliorates salinity stress. Appl. Soil Ecol. 96: 114-121.

Hassani, A., A. Azapagic and N. Shokri. 2020. Predicting long-term dynamics of soil salinity and sodicity on a global scale. Proc. Natl. Acad. Sci. U.S.A. 117: 33017-33027.

Heiss, J. W., B. Mase and C. Shen. 2022. Effects of future increases in tidal flooding on salinity and groundwater dynamics in coastal aquifers. Water Resour. Res. 58: e2022WR033195.

Hintz, W. D., S. E. Arnott, C. C. Symons, D. A. Greco, A. McClymont, J. A. Brentrup, M. Cañedo-Argüelles, A. M. Derry, A. L. Downing, D. K. Gray. 2022. Current water quality guidelines across North America and Europe do not protect lakes from salinization. Proc. Natl. Acad. Sci. U.S.A. 119: e2115033119.

Hong, C., J. A. Burney, J. Pongratz, J. E. M. S. Nabel, N. D. Mueller, R. B. Jackson and S. J. Davis. 2021. Global and regional drivers of land-use emissions in 1961–2017. Nature. 589: 554-561.

Hopmans, J. W., A. S. Qureshi, I. Kisekka, R. Munns, S. R. Grattan, P. Rengasamy, A. Ben-Gal, S. Assouline, M. Javaux, P. S. Minhas et al. 2021. Chapter One - Critical knowledge gaps and research priorities in global soil salinity. In: D. L. Sparks ed. *Advances in Agronomy. p.* 1-191. Academic Press.

Huang, Y., X. Lee, M. Grattieri, M. Yuan, R. Cai, F.C. Macazo and S.D. Minteer. 2020. Modifid biochar for phosphate adsorption in environmentally relevant conditisons. Chem. Eng. J. 380:122375.

Isayenkov, S. V. 2019. Genetic sources for the development of salt tolerance in crops. Plant Growth Regul. 89: 1-17.

Jensen, L., J. Schjoerring and K. van der Hoek. 2011. Benefits of nitrogen for food fibre and industrial production. In: Sutton MA, Howard CM, Erisman JW, Billen G, Bleeker A, Grennfelt P, Grinsven Hv, Grizzetti B editors 2011. The European nitrogen assessment: sources, effects and policy perspectives 2011 Cambridge, UK: Cambridge University Press. 32–61.

Karim, A. A., M. Kumar, E. Singh, A. Kumar, S. Kumar, A. Ray and N. K. Dhal, 2022: Enrichment of primary macronutrients in biochar for sustainable agriculture: A review. Crit. Rev. Environ. Sci. Technol. 52: 1449-1490.

Kaushal, S. S., G. E. Likens, M. L. Pace, J. E. Reimer, C. M. Maas, J. G. Galella, R. M. Utz, S. Duan, J. R. Kryger, A. M. Yaculak et al. 2021. Freshwater salinization syndrome: from emerging global problem to managing risks. Biogeochemistry. 154: 255-292.

Khadem, A., F. Raiesi, H. Besharati and M. A. Khalaj. 2021. The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar 3, 105-116.

Khan, K., M. Ali, M. Naveed, M. Rehmani, M. Shafique, H. Ali, N. Abdelsalam, R. Ghareeb and G. Feng, 2022: Co-application of organic amendments and inorganic P increase maize growth and soil carbon, phosphorus availability in calcareous soil. Front. Environ. Sci. , 10:949371.

Kim, H.S., K.R. Kim, J.E. Yang, Y.S. Ok, G. Owens, T. Nehls, G. Wessolek and K.H. Kim 2016. Effect of biochar on reclaimed tidal land soil properties and maize (*Zea mays* L.) response. Chemosphere. 142:153–159.

Kumar, A. and J.P Verma. 2018. Does plant-microbe interaction confer stress tolerance in plants: A review? Microbiol Res. 207:41–52.

Lashari, M.S., Y. Liu, L. Li, W. Pan, J. Fu, G. Pan and X. Yu. 2013. Effects of amendment of biochar manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a saltstressed cropland from Central China Great Plain. Field Crop Res. 144:113–118.

Lashari, M.S., Y. Ye, H. Ji, L. Li, G.W. Kibue, H. Lu, J. Zheng and G. Pan. 2015. Biochar–manure compost in conjunction with pyroligneous solution alleviated salt stress and improved leaf bioactivity of maize in a saline soil from central China: a 2-year field experiment. J. Sci. Food Agric. 95: 1321–1327.

Lassiter, A. 2021. Rising seas, changing salt lines, and drinking water salinization. Curr. Opin. Environ. Sustain. 50: 208-214.

Lehman, J., M.C. Rilling, J.E. Thies, C.A. Masiello, W.C. Hockaday and D. Crowley. 2011. Biochar effects on soil biota—a review. Soil Biol. Biochem. 43:1812–1836.

Liang, X., X. Wang, N. Zhang and B. Li. 2022. Biogeographical patterns and assembly of bacterial communities in saline soils of Northeast China. Microorganisms. 10: 1787.

Lin, X.W., Z.B. Xie, J.Y. Zheng, Q. Liu, Q.C. Bei and J.G. Zhu. 2015. Effects of biochar application on greenhouse gas emissions, carbon sequestration and crop growth in coastal saline soil. Eur. J. Soil Sci. 66: 329–338.

Liu, S., J. Meng, L. Jiang, X. Yang, Y. Lan, X. Cheng and W. Chen. 2017. Rice husk biochar impacts soil phosphorous availability, phosphatase activities and bacterial community characteristics in three different soil types. Appl. Soil Ecol. 116: 12–22.

Llamas, D.P., M.D. Gonzales, C.I. Gonzales, G.R. Lopez and J.C. Marquina 2008. Effects of water potential on spore germination and viability of Fusarium species. J. Indust. Microbiol. Biotechnol. 35(11):1411-1418.

Luo, X., G. Liu, Y. Xia, L. Chen, Z. Jiang, H. Zheng and Z. Wang. 2017. Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. J. Soils Sediments. 17(3): 780-789.

Maathuis, F.J., I. Ahmad and J. Patishtan. 2014. Regulation of Na+ fluxes in plants. Front Plant Sci. 5:467.

Maertens, M., G. J. M. De Lannoy, F. Vincent, S. Massart, R. Giménez, J. Houspanossian, I. Gasparri and V. Vanacker. 2022. Spatial patterns of soil salinity in the central Argentinean Dry Chaco. Anthropocene. 37: 100322.

Mahmood, M. Z., S. Bibi, M. Shahzad, A. Fakhar, M. Rafique and A. Qayyum. 2021. Mechanisms of microbes to combat salinity in soil by producing secondary metabolites. Arabian J. Geosci. 15: 45.

Mahmoud, E., T. El-Beshbeshy, N.A. El-Kader, R.E. Shal and N. Khalafallah. 2019 Impacts of biochar application on soil fertility, plant nutrients uptake and maize (*Zea mays* L.) yield in saline sodic soil. Arab J. Geosci. 12(23):1–9.

Mamilov, A.S. and O.A. Dilly. 2002. Soil microbial eco-physiology as affected by shortterm variations in environmental conditions. Soil Biol. Biochem. 34:1283-1290.

Mandeel, Q.A. 2006. Biodiversity of the genus Fusarium in saline soil habitats. J. Basic Microbiol. 46(6):480-494.

Martí, E., J. Sierra, X. Domene, M. Mumbrú, R. Cruañas and M. A. Garau. 2021. One-year monitoring of nitrogen forms after the application of various types of biochar on different soils. Geoderma. 402: 115178.

Meng, X., J. Zhou and N. Sui. 2018. Mechanisms of salt tolerance in halophytes: Current understanding and recent advances. Open Life Sci. 13:149–154.

Mohan, D., A. Sarswat, Y.S. Ok and C.U Pittman. 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresour Technol. 160:191–202.

Mohanavelu, A., S. R. Naganna and N. Al-Ansari. 2021. Irrigation Induced Salinity and Sodicity Hazards on Soil and Groundwater: An Overview of Its Causes, Impacts and Mitigation Strategies. Agriculture. 11: 983.

Munns, R. 2002. Comparative physiology of salt and water stress. Plant, Cell & Environment. 25:239-250.

Murtaza, G., Z. Ahmed, M. Usman, W. Tariq, Z. Ullah, M. Shareef, H. Iqbal, M. Waqas, A. Tariq, Y. Wu, Z. Zhang and A. Ditta. 2021. Biochar induced modifications in soil properties and its impacts on crop growth and production. J. Plant Nutrit. 44: 1677-1691.

Nath, H., B. Sarkar, S. Mitra and S. Bhaladhare. 2022. Biochar from biomass: A review on biochar preparation its modification and impact on soil including soil microbiology. Geomicrobiol. J. 39: 373-388.

Naz, T., M.M. Iqbal, M. Tahir, M. M. Hassan, M. I. A. Rehmani, M. I. Zafar, U. Ghafoor, M. A. Qazi, A. EL Sabagh and M. I. Sakran. 2021. Foliar application of potassium mitigates salinity stress conditions in spinach (*Spinacia oleracea* L.) through reducing NaCl toxicity and enhancing the activity of antioxidant enzymes. Horticulturae. 7: 566.

Negacz, K., Ž. Malek, A. de Vos and P. Vellinga. 2022. Saline soils worldwide: Identifying the most promising areas for saline agriculture. J. Arid Environ. 203: 104775.

Niazi, N.K., B. Murtaza, I. Bibi, M. Shahid, J.C. White, M.F. Nawaz, S. Bashir, M.B. Sakoor, G. Choppala, G. Murtaza and H. Wang. 2016. Removal and Recovery of Metals by Biosorbents and Biochars Derived from Biowastes. Environmental Materials and Waste, Elsevier. p.149–177.

O'Connor, G.A., H.A. Elliott and P.K. Bastian. 2008. Degraded water reuse: An overview. J. Environ. Qual. 37(5):157–168.

Okur, B. and N. Örçen. 2020. Chapter 12 - Soil salinization and climate change. In: M. N. V. Prasad and M. Pietrzykowski eds. *Climate Change and Soil Interactions.* Elsevier, *p.* 331-350.

Olson, S., M. F. Jansen, D. S. Abbot, I. Halevy and C. Goldblatt. 2022. The Effect of Ocean Salinity on Climate and Its Implications for Earth's Habitability. Geophys. Res. Lett. 49: e2021GL095748.

Ondrasek, G. and Z. Rengel. 2021. Environmental salinization processes: Detection, implications & solutions. Sci. Total Environ. 754: 142432.

Palansooriya, K. N., J. T. F. Wong, Y. Hashimoto, L. Huang, J. Rinklebe, S. X. Chang, N. Bolan, H. Wang and Y. S. Ok. 2019. Response of microbial communities to biochar-amended soils: a critical review. Biochar 1: 3-22.

Panchasara, H., N. H. Samrat and N. Islam. 2021. Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review. Agriculture. 11: 85.

Parthasarathy, P., T. Al-Ansari, H. R. Mackey, K. Sheeba Narayanan and G. McKay. 2022. A review on prominent animal and municipal wastes as potential feedstocks for solar pyrolysis for biochar production. Fuel. **316:** 123378.

Penn, C. J. and J. J. Camberato, 2019. A critical review on soil chemical processes that control how soil ph affects phosphorus availability to plants. Agriculture 9: 120.

Prăvălie, R. 2021. Exploring the multiple land degradation pathways across the planet. Earth-Sci. Rev. 220: 103689.

Premarathna, K.S.D., A.U., Rajapaksha, Sarkar B, E.E., Kwon, A., Bhatnagar, Y.S., Ok and M., Vithanage 2019. Biochar-based engineered composites for sorptive decontamination of water: a review. Chem. Eng. J. 372: 536–550

Qiu, B., X. Tao, H. Wang, W. Li, X. Ding and H. Chu. 2021. Biochar as a low-cost adsorbent for aqueous heavy metal removal: A review. J. Anal. Appl. Pyrolysis. 155: 105081.

Quilty, J.R. and S.R. Cattle. 2011. Use and understanding of organic amendments in Australian agriculture: a review. Soil Res. 49:1–26.

Rahman, A.K.M.M., K.M. Ahmed, A.P. Butler and M.A. Hoque. 2018. Influence of surface geology and micro-scale land use on the shallow subsurface salinity in deltaic coastal areas: a case from southwest Bangladesh. Environ. Earth. Sci. 77:423.

Rahman, G. K. M. M., M. M. Rahman, M. S. Alam, M. Z. Kamal, H. A. Mashuk, R. Datta and R. S. Meena. 2020. Biochar and Organic Amendments for Sustainable Soil Carbon and Soil Health. In: R. Datta, R. S. Meena, S. I. Pathan and M. T. Ceccherini eds. *Carbon and Nitrogen Cycling in Soil.* Springer Singapore, Singapore, p. 45-85.

Rajkovich, S., A. Enders, K. Hanley, C. Hyland, A.R. Zimmerman and J. Lehmann. 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol. Fertil. Soils. 48:271-284.

Rasheed, S., S. Jahan, T. Sharmin, S. Hoque, M.A. Khanam, M.A. Land and A. Bhuiya. 2014. How much salt do adults consume in climate vulnerable coastal Bangladesh? BMC Public Health. 14(1):1–7.

Rengasamy, P. 2016. Soil chemistry factors confounding crop salinity tolerance—A review. Agronomy. 6: 53.

Rezaei, N. and F. Razzaghi. 2018. Effect of different levels of water salinity and biochar on wheat yield under greenhouse conditions. Acta. Horticulturae. 1190:83-88.

Richards, L. A. 1954. Diagnosis and improvement of saline and alkali soils. Handbook No. 60. US Department of Agriculture.

Rizwan, M., S. Ali, M.F. Qayyum, M. Ibrahim, M.Z. Rehman, T. Abbas and Y.S. Ok. 2016. Mechanisms of biochar-mediated alleviation of toxicity of trace elements in plants: a critical review. Environ. Sci. Pollut. Res. 23:2230–2248.

Ros, M. B. H., G. F. Koopmans, K. J. van Groenigen, D. Abalos, O. Oenema, H. M. J. Vos and J. W. van Groenigen. 2020. Towards optimal use of phosphorus fertiliser. Sci. Rep. 10, 17804.

Roy, S. and N. Chowdhury. 2020. Salt Stress in Plants and Amelioration Strategies: A Critical Review. In: F. Shah, S. Shah, C. Yajun, W. Chao and W. Depeng eds. *Abiotic Stress in Plants.* Ch. 19. IntechOpen, Rijeka.

Sabino, M., E. Schefuß, M. Natalicchio, F. Dela Pierre, D. Birgel, D. Bortels, B. Schnetger and J. Peckmann. 2020. Climatic and hydrologic variability in the northern Mediterranean across the onset of the Messinian salinity crisis. Palaeogeograph. Palaeoclimatol. Palaeoecol. 545: 109632.

Sadegh-Zadeh F., M. Parichehreh, B. Jalili and M.A. Bahmanyar. 2018. Rehabilitation of calcareous saline-sodic soil by means of biochars and acidified biochars, Land Degradation and Development. 29(10): 3262-3271.

Saifullah, S.D., A. Naeem, Z. Rengel and R. Naidu. 2018. Biochar application for the remediation of salt affected soils: Challenges and opportunities. Sci. Total Environ. 625:320-335.

Sakhiya, A. K., A. Anand, I. Aier, V. K. Vijay and P. Kaushal. 2021. Suitability of rice straw for biochar production through slow pyrolysis: Product characterization and thermodynamic analysis. Biores. Technol. Report. 15: 100818.

Sarfraz, R., A. Hussain, A. Sabir, I. Ben Fekih, A. Ditta and S. Xing. 2019. Role of biochar and plant growth promoting rhizobacteria to enhance soil carbon sequestration—a review. Environ. Monitor. Assessm. 191:, 251.

Schuler, M. S., M. Canedo-Argüelles, W. D. Hintz, B. Dyack, S. Birk and R. A. Relyea. 2019. Regulations are needed to protect freshwater ecosystems from salinization. Philos. Trans. Royal Soc. B. 374: 20180019.

Shakoor M.B., Z.L. Ye, S. Chen. 2021. Engineered biochars for recovering phosphate and ammonium from wastewater: a review. Sci. Total. Environ. 779: 146240.

Sigua, G. C., J. M. Novak, D. W. Watts, K. B. Cantrell, P. D. Shumaker, A. A. Szögi and M. G. Johnson. 2014. Carbon mineralization in two ultisols amended with different sources and particle sizes of pyrolyzed biochar. Chemosphere.**103:** 313-321.

Singh, A., 2022. Soil salinity: A global threat to sustainable development. Soil Use Manag. 38: 39-67.

Singh, J. S. and V. K. Gupta. 2018. Soil microbial biomass: A key soil driver in management of ecosystem functioning. Sci. Total Environ. 634: 497-500.

Singh, R, A. Prakash, B. Balagurumurthy, R. Singh, S. Saran and T. Bhaskar. 2015. Hydrothermal liquefaction of agricultural and forest biomass residue: comparative study. J. Mater Cycles Waste Manag. 17: 442–452.

Sun, H., H. Lu, L. Chu, H. Shao and W. Shi. 2017. Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH_3 volatilization in a coastal saline soil. Sci. Total Environ. 575: 820–825.

Tabari, H. 2021. Extreme value analysis dilemma for climate change impact assessment on global flood and extreme precipitation. J. Hydrol. 593: 125932.

Tanu, F. Z. 2022. Imbalanced nutrient accumulation in the coastal soils induced by salinity intrusion. Polish J. Soil Sci. 55: 37-49.

Thomas S.C., S. Frye, N. Gale, M. Garmon, R. Launchbury, N. Machado, S. Melamed, J. Murray, A. Petroff and C. Winsborough. 2013. Biochar mitigates negative effects of salt additions on two herbaceous plant species, J. Environ. Manage. 129: 62-68.

Tripathi, S., S. Kumari, A. Chakraborty, A. Gupta, K. Chakrabarti and B.K. Bandyapadhyay. 2006. Microbial biomass and its activities in salt-affected coastal soils. Biol. Fert. Soils. 42:273–277.

Tubiello, F. N., K. Karl, A. Flammini, J. Gütschow, G. Obli-Laryea, G. Conchedda, X. Pan, S. Y. Qi, H. Halldórudóttir Heiðarsdóttir, et al. 2022. Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. Earth Syst. Sci. Data. 14: 1795-1809.

Wicke, B., E. Smeets, V. Dornburg, B. Vashev, T. Gaiser, W. Turkenburg and A. Faaij. 2011. The global technical and economic potential of bioenergy from salt-affected soils. Energy Environ. Sci. 4:2669-2681.

Winkler, K., R. Fuchs, M. Rounsevell and M. Herold. 2021. Global land use changes are four times greater than previously estimated. Nat. Commun. 12: 2501.

Woolf, D., J.E. Amonette, F.A. Street-Perrott, J. Lehman and S. Joseph. 2010. Sustainable biochar on mitigate global climate change. Nat. Commun. 1:56.

World Health Organization. 2015. Cardiovascular Diseases. Available from: www.who.int/mediacentre/factsheets/fs317

Wu, S., H. He, X. Inthapanya, C. Yang, L. Lu, G. Zeng and Z. Han. 2017. Role of biochar on composting of organic wastes and remediation of contaminated soils-a review. Environ. Sci. Pollut. Res. 24(20):16560–16577.

Xu, H., A. Cai, D. Wu, G. Liang, J. Xiao, M. Xu, G. Colinet and W. Zhang. 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 Till. Res. 213: 105125.

Yan, N. and P. Marschner. 2013. Microbial activity and biomass recover rapidly after leaching of saline soils. Biol. Fertil. Soils. 49:367-371.

Yan, N., P. Marschner, W. Cao, C. Zuo and W. Qin. 2015. Influence of salinity and water content on soil microorganisms. Int. Soil Water Conserv. Res. 3: 316-323.

Yang, D., Y. Yang and J. Xia. 2021. Hydrological cycle and water resources in a changing world: A review. Geogr. Sustain. 2: 115-122.

Yasir, T. A., A. Khan, M. Skalicky, A. Wasaya, M. I. A. Rehmani, N. Sarwar, K. Mubeen, M. Aziz, M. M. Hassan, F. A. S. Hassan et al., 2021. Exogenous sodium nitroprusside mitigates salt stress in lentil (*Lens culinaris* Medik.) by affecting the growth, yield, and biochemical properties. Molecules. 26: 2576.

Yin, X., Q. Feng, Y. Li, R. C. Deo, W. Liu, M. Zhu, X. Zheng and R. Liu. 2022. An interplay of soil salinization and groundwater degradation threatening coexistence of oasis-desert ecosystems. Sci. Total Environ. 806: 150599.

Yue, Y., W.N. Guo, Q.M. Lin, G.T. Li and X.R. Zhao. 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. 71:467-475

Zhang, Q., B.J. Liu, Y.U. Lu, R.R. Wang and F.M. Li. 2019. Effects of biochar amendment on carbon and nitrogen cycling in coastal saline soils: a review. J Nat. Resourc. 34(12):2529–2543.

Zhao, Y., X. Zhuang, S. Ahmad, S. Sung and S.-Q. Ni. 2020. Biotreatment of high-salinity wastewater: current methods and future directions. World J. Microbiol. Biotechnol. 36: 37.

Zheng, X., W. Xu, J. Dong, T. Yang, Z. Shangguan, J. Qu, X. Li and X. Tan. 2022. The effects of biochar and its applications in the microbial remediation of contaminated soil: A review. J. Hazard. Mater. 438: 129557.

Zou, Q., W.H. An, C. Wu, W. Li, A. Fu and S. Xue. 2017. Red mud-modified biochar reduces soil arsenic availability and changes bacterial composition. Environ. Chem. Lett. 16: 615–622.