CONSTRAINTS IN SALT-AFFECTED SOIL AND THEIR MANAGEMENT THROUGH BIOCHAR APPLICATION: A REVIEW

DHANUSHKODI, V.[1] – NAGESWARI, R.[2*] – ANITHA, R.[3] – ARULSELVI, S.[1] – PERIYAR RAMASAMY, D.[1] – SANGEETHA, S.[4] – KARUNAKARAN, V.[1] – SHENBAGAVALLI, S.[5] – AMUTHASELVI, G.[6] – SANGEETHA, M.[7] – RATHIKA, S.[8] – JANAKI, D.[8] – ANURATHA, D.[9] – THANGA HEMAVATHY, A.[8] – SABAPATHI, M.[1] – YAMUNARANI, K.[4]

[1]ICAR-Krishi Vigyan Kendra, Thiruvarur 614404, Tamil Nadu, India

[2]Tamil Nadu Rice Research Institute, Thanjavur 612101, Tamil Nadu, India

[3]Sugarcane Research Station, Cuddalore 607 001, Tamil Nadu, India

[4]Horticultural College and Research Institute for Women, Trichy 620027, Tamil Nadu, India

[5]Horticultural College and Research Institute, Periyakulam 625601, Tamil Nadu, India

[6]Agricultural Engineering College and Research Institute, Coimbatore 641003, Tamil Nadu, India

[7]Regional Research Station, Dharmapuri 635112, Tamil Nadu, India

[8]Anbil Dharmalingam Agricultural College and Research Institute, Trichy 620027, Tamil Nadu, India

[9]Agricultural College and Research Institute, Nagappattinam 611001, Tamil Nadu, India

[*]Corresponding author
e-mail: oryzanagtn@gmail.com; dhanushkodi@tnau.ac.in

(Received 23rd Jul 2024; accepted 4th Nov 2024)

Abstract. Plant growth is restricted in soils that have salinity and sodicity problems. In arable farming, salinity of soils is the most common threat to soil productivity. Salt-affected soil is a widespread issue that affects more than 100 countries worldwide. If we are to tackle the challenges of global food security, we have to cultivate barren salt-affected soils. Soil affected by salt can be reclaimed using inorganic and organic sources. The choice of an ameliorant for a given site depends largely on its geographical and physicochemical characteristics. Currently, biochar is a popular soil amendment. Salt-affected soils can be improved physically, chemically, and biologically by adding biochar. As a result of the biochar application, drought-stressed and salt-stressed plants increased their growth, biomass, nutrient uptake, and yield. Uptake of sodium by plants was decreased by biochar when exposed to salt stress, but it was increased by potassium. An increase in tolerance to salt by plant can be attributed to soil properties, reduce sodium uptake, improved nutrients uptake, and regulate phyto-hormones levels and stomata opening and closing. Throughout this paper, the main focus was to review the constraints in salt-affected soil and discuss recent studies related to the effects of biochar on soil properties and plant growth. Further information was also provided on the functions of biochar as a soil amendment, and its interactions with soil and plants to overcome problems and improve crop yield.
Keyword: *problem soil, amendments, nutrient availability, crop yield*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Introduction

Global crop production is threatened by excessive salt and sodicity in the soil, which affects over 7% of the world's land surface and is projected to cost $12 billion annually to the agricultural sector (Qadir et al., 2014). According to the Food and Agriculture Organization, salinity was anticipated to affect over 800 million hectares, causing a major restriction on food production for a rapidly expanding population. It is important to cultivate more crops to meet our future demographic needs, and this requires using salt-affected land and saline water effectively. Irrigation accounts for almost 70% of all freshwater usage worldwide. Salt-affected and saline water irrigated land composes at least 20% of the world's irrigated land (Shrivastava and Kumar, 2015). Salinity also affects approximately two million hectares of cropland annually (Munns and Gilliham, 2015). 50% of cropping acreage is expected to be lost by the middle of the 21st century because of salinization. It is important to note that these problems also exist in some of the world's subhumid and humid regions, especially along the coast (Ehtaiwesh, 2022). Aside from salinization, approximately 30% of irrigated croplands worldwide suffer from drought (Chaves et al., 2009). As a result of high temperatures during summer in arid regions, huge amounts of salts are left behind because of evaporation losses. Arid and semiarid climates normally produce soils containing high salts. However, salinity problems occur when salts accumulate in the crop root zone causing a loss of yield (Ehtaiwesh, 2022).

Poor drainage, low rainfall, and high evaporation contribute to excessive salt accumulation in the root and decrease low yields. Consequently, saline and sodic soils have low organic matter status and it prone to erosion due to poor plant growth (Rengasamy et al., 2022). Saline soils also suffer from osmotic stress, which reduces microbial growth. In contrast, sodic soils are subjected to ion toxicities and a high pH, both are unfavourable for the microbial community. Salt-affected soils need to be cultivated to address challenges associated with global food security (Saifullah et al., 2018; Ehtaiwesh, 2022). Organic amendments have been suggested to improve soil properties in high salinity conditions by many researchers. Organic matter addition to salt-affected soils results in a decrease in the exchangeable sodium percentage (ESP) and an improvement in water movement, water-holding capacity (WHC), stability of aggregate, and soil microbial biomass (Wu et al., 2015). Depending on their chemical composition, organic amendments may regenerate salt-affected soils in different ways and therefore may affect the properties of these soils in different ways. It is reasonable and reliable to employ biochar as an amendment to implement soil remediation because it contains a multitude of beneficial properties (Chahal et al., 2017).

As a soil amendment, biochar (solid carbonaceous residue produced at temperatures ranging from 300 to 1000°C without oxygen or oxygen-limited conditions) has recently gained notable attention. Biochar addition improves salt-affected soil's properties (Saifullah et al., 2018). Among the many uses of biochar, it is well known as a source of divalent cations due to its carbon-rich nature and rapid thermal degradation at low temperatures under a limited supply of oxygen (Laird et al., 2009). As an example, Biochar added at a rate of 20 tonnes per hectare significantly increased calcium and magnesium availability in *Oxisols* (Khan et al., 2024). In soils, these cations could replace sodium for leaching, which could help to improve soil structure. Biochar application reduces bulk density, improves soil aeration, aggregate stability, and facilitates water infiltration. The primary focus of this paper was to review the

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

constraints in salt-affected soil and discuss recent studies related to the effects of biochar on soil properties and plant growth.

Salt-affected soils

Salt-affected soils typically contain high concentrations of dissolved salts, primarily sodium chloride, calcium chloride, magnesium chloride, and sulfate chlorides. ESP (exchangeable sodium percentage) of saturated paste extracts uses pH, EC, SAR (sodium adsorption ratio), and ESP to identify if salt-affected soils are saline, sodic, or saline-sodic (*Fig. 1*). Plant growth is impeded by salt-affected soils due to two factors: (a) osmotic stress, which lowers plant water absorption; and (b) specific ion impacts, which prevent plants from receiving necessary ions (Atta et al., 2023). A salty soil solution adversely affects the soil biota and vegetation due to its altered osmotic and matrix potentials (Dang et al., 2017). Conversely, sodicity alters soil properties, causing deterioration in soil structure, lower water permeability, water penetration, and hydraulic conductivity. Moreover, sodic areas are characterized by erosion, as well as prolonged periods of water stagnation and altered hydrologic reactions (Bhattacharyya et al., 2016; Ehtaiwesh, 2022).

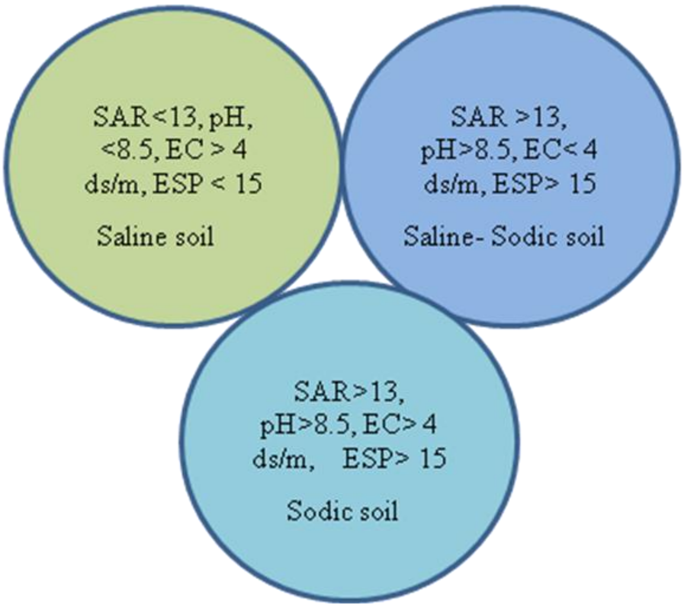

Figure 1. *Types of salt-affected soils (Singh et al., 2019)*

Influence of salts on soil characteristics

The adverse effects on soil properties may be greatly diminished or nonexistent in soils containing small quantities of exchangeable sodium (e.g., exchangeable sodium of 0.7 me/100 g) and low cation exchange capacities (*Table 1*). Soils with coarse textures (sandy) may have fewer restrictions on permeability and may tolerate water with a greater SAR.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Table 1. *Various constraints exist in saline and sodic soil*

S. No.	Problems	References
1.	Soil particle disperses and reduces structural stability	(Rengasamy et al., 2022)
2.	Less nutrient availability, nutrient deficiencies, competitive uptake, transport, and partitioning within plants	(Bidalia et al., 2019)
3.	Calcium and potassium deficiency due to ion activities and extreme ion ratios	(Ehtaiwesh, 2022)
4.	Competing nutrients in sodic soils, result in potassium deficiency (K) and phytotoxicity of sodium (Na), aluminium (Al), and iron (Fe)	(Nguyen et al., 2022)
5.	High chloride concentration reduces N uptake	(Yasuor et al., 2020)
6.	Reduce symbiotic N_2 fixation systems	(Egamberdieva et al., 2018)
7.	Reduce macronutrient nutrient availability	(Das et al, 2023)
8.	Phosphorus (P), potassium (K), and nitrogen (N) deficiency	(Nguyen et al., 2022)
9.	Osmotic stress and dehydration due to salt	(Bidalia et al., 2019)
10.	Reduction in microbial population and activity, including salt stress, sodium toxicity, nutritional deficiency, CO_3^-, HCO_3^-, and Cl^- levels, as well as loss of organic matter from the degradation of the structure	(Chahal et al., 2017; Bidalia et al., 2019)
11.	Adverse effects on their microbial communities (Fungus population than bacteria) due to elevated soluble salt content	(Li et al., 2021)
12.	Negative effect on microbial and biochemical activity in soil	(Amini et al., 2016)
13.	The low inputs and high losses of organic matter result in poor organic matter content	(Mohanavelu et al., 2021)
14.	Decreased soil organic carbon and total nitrogen content	(Hassani et al., 2024)
15.	Dispersion of soil aggregates, which triggers the decomposition of that organic matter	(Abdul Rahman et al., 2021)
16.	Mineralization rates like C and N are reduced	(Zhang et al., 2019)
17.	Reduced soil enzyme activity and mineralization of N, C, P, and S	(Zhang et al., 2019)
18.	Poor soil structural stability due to adsorbed (exchangeable) sodium	(Rengasamy et al., 2022)

Salts' effect on crop growth

Among the different stresses that salinity and sodicity affect germination, crop growth, and yield is salinity (*Table 2*). Crop yields and crop suitability are affected by soil salinity, as are plant nutrient availability, plant nutrient uptake, and soil microorganism activity (Murad Muhammad et al., 2023). It has been shown that salinity adversely affects crop plants via osmotic stress, resulting in a reduction in water availability; and ionic stress, which changes the cell ionic balance, which is leading to nutrient deficiencies and toxicity (Hazman et al., 2016). Among the factors that affect nutrient availability and uptake in saline environments are factors related to soil and plants (Ehtaiwesh, 2022).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Table 2. *Negative effects of salts in soil on crop growth*

S. No.	Particulars	References
1.	Salt damage crop during the early seedling stage	(Ehtaiwesh and Rashed, 2019)
2.	Lesser damage during seed germination compared to the seedling stage	(Ehtaiwesh and Rashed, 2019)
3.	Reduction in an entire plant's biomass and yield because of salts, as well as a reduction in the number of cells and leaf area due to salts	(Giuffrida et al., 2013)
4.	Net CO_2 assimilation and water use efficiency were reduced	(Dourado et al., 2022; Al Hinai et al., 2022)
5.	Elevated CO_2 of salt stress causes chlorophyll concentrations and photosynthesis system II	(Melgar et al., 2008)
6.	Salinity affects plant hormone production	(Mohammad Khani et al., 2018)
7.	Abscisic acid receptors are increased in the leave	(Shah et al., 2023)
8.	Acetyl Salicylic (Aspirin) alleviated the injuries caused by salinity stress	(Ehtaiwesh, 2022)
9.	Salt contamination damages plant roots	(Bernstein, 2019)
10.	Salinity affects root growth and soil penetration	(Vaishnavi et al., 2024)
11.	Crop yield reduced	(Atta et al., 2023)
12.	Excessive soil moisture, combined with high soluble salt levels in the root zone, is either limited or prevented	(Tarolli et al., 2024)
13.	Water movement in the soil to the roots is slowed by more salt.	(Lu and Fricke, 2023)
14.	Salt affects fresh weight, chlorophyll content, and electrolyte leakage, antioxidant power, soluble proteins, free amino acids, and mineral content in plants	(Fedeli et al., 2024)

Knowledge gap which needs new insights

Through research on the long term impacts of plant-soil interaction should be done using a multidisciplinary approach in soil science, plant pathology, plant physiology, microbiology, and soil salinity under various climate scenarios. Effective design for mitigation and adaptation strategies in the face of climate change, future work should concentrate on building predictive models that replicate, plant-soil interactions under salinity stress (Hao Tang et al., 2024). To determine precise salt levels and how to control them, it is necessary to conduct more frequent and accurate salinity surveys while exploring new areas with saline soil. To more fully assess the suitability of soils and define the suitable area for salt-tolerant crops, research on mapping saline soils should test other important criteria, such as soil type (especially divisions between clay, loamy, and sandy soils), the occurrence of brackish groundwater, and crop growing requirements in specific countries (Katarzyna Negacz et al., 2022). In order to maximize the chances of reclamation success, land affected by salt should rely more on modeling techniques (Shaygan et al., 2022). Instead of viewing soil health as only a variable to be measured, researchers should view it as a general concept to advance knowledge. This would help to establish soil health as a topic of study to which a wide range of disciplines can contribute. One method to do this would be to list the research conducted on each subject under the keyword “soil Health”. It will take cooperation

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

from all parties concerned, especially a shared understanding between scientists and stakeholders, to let the soil health concept fulfil its potential as a unifying idea that incorporates soil functions (Lehmann et al., 2020). At present, there exists an incomplete understanding of the most efficient ways to enhance saline-sodic soils to facilitate sustainable agricultural production. This is particularly evident in the absence of a systematic examination of the impacts of various amendments on a worldwide level (Wand et al., 2024).

It takes a deep understanding of resource conservation and efficient use to restore salty and alkaline soils, stop further growth, and manage soil and water. The absence of scientific information and locally applicable solutions is the primary obstacle to managing and reclamating soil in arid lowland areas. As a result, the following research directions regarding the management of saline and sodic soils are advised: to examine the physical, mineralogy or colloids, chemistry, biology, and other environmental, economic, and social factors affecting soil salinity and sodicity as well as their relationships; to forecast potential damages resulting from the growing issues with salinity and sodicity; to educate farmers about the processes of salinisation and alkalisation and to develop plans for preparedness against these issues. It is necessary to look at the initial sources of the salt-containing elements in the nation's irrigation water supplies and soils affected by salt. Based on the findings of several fieldwork and laboratory investigations, we must identify and categorize salt-affected soils into several types and classes (Stavi Illan et al., 2021). Maps of salt-affected soils at the zonal, regional, and national levels must be created using reconnaissance and a thorough analysis of dryland and irrigated soils. Technologies that are easily accessible must be updated, made more widely known, and helped to reach end users. To serve as guidelines for better water management techniques, we must create agricultural water management manuals and bulletins (Stavi Illan et al., 2021). Exchangeable Na+ was swapped out for inorganic modifications, which reduced.

To completely understand C dynamics in salt-affected soils, studies on the impact on C stocks and fluxes are necessary to pinpoint the crucial problems about the breakdown of soil organic matter and soil aggregation processes (Wong et al., 2010). In order to generalize results to other comparable areas, computer modeling may be used to evaluate the economic viability of various soil amelioration techniques. Furthermore, computer modeling has proven to be a potentially helpful addition to experimental data to stimulate the mobility and interaction of salt in sodic soils. But these models must be tested in real-world settings (Qadir et al., 2001). Enhancing the sensing techniques beyond retrieval systems is also recommended in order to enable large-scale direct detection of salinization and water logging characteristics. By utilizing data from numerous satellite, which reduces spatial resolution issues by boosting system efficiency, it is also advised that current time lag between the occurrence and recording various data be improved in future. Future research is required to address the environmental issues of soil salinisation and waterlogging in irrigated areas caused by inadequate drainage (Singh et al., 2021).

To effectively address salt stress and ecosystem degradation, future research should clarify certain important issues, such as: (1) What is the tipping point for the reaction of various soil microbial elements in saline and non-saline soils? (2) How do microorganisms interact with upper trophic levels (such as nematodes) and with each other under salt stress, and how can their interactions be used to guide the maintenance of ecosystem diversity and intelligent agricultural production? (3) How can

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

environmental conditions be altered to modulate microbial diversity and functions under human control (Zhang et al., 2021)? Future studies are required to understand the relationships between monovalent and bivalent cations in soil solution and CEC, as well as how these interactions affect the clay fraction about soil slaking, dispersion, and swelling. More research should be focused on better conceptual and physically grounded semi-empirical models that describe how salinity and sodicity affect the hydraulic characteristics of soil. Establishing techniques for estimating a soil's net dispersive charge so that they can be used in modelling the reclamation of sodic soils (Jan et al., 2021).

Biochar

Carbon-rich biochar is created by heating biomass inside a closed container without air. Biochar is formed by the degradation of organic materials at low temperatures and under limited oxygen supply. Several factors contribute to the high stability of carbon structures (Zhan et al., 2019; Nguyen et al., 2022). The physical and chemical properties of biochar can vary depending on the feedstock and the pyrolysis conditions. It is important to consider the biochemical composition (lignin, cellulose, hemicellulose), dust particles, and moisture content of biomass when determining the properties of pyrolyzed biochar (Al-Rumaihi et al., 2022). As an example, wood-derived biochar has a higher total carbon content, lower ash content, higher total N, P, K, S, calcium, magnesium, aluminum, and sodium contents, and higher cation exchange capacity (CEC) than manure-derived biochar.

In other words, by sequestering carbon from the soil, biochar can mitigate climate change effectively (Lehmann et al., 2021). In addition to reducing carbon emissions, biochar also enhances soil properties (physically, chemically, and biologically). In addition, it improves particle size distribution and reduces the bulk density of soil (Yadav et al., 2023). Aside from this, biochar's high CEC and water-holding capacity allow it to improve the water status of plants as well as reduce the negative effects of contaminated soils (Nguyen et al., 2023). Soil damage caused by salt may be remedied by biochar as a soil amendment. Even though biochar has been used worldwide, it is effective when applied to non-saline, non-sodic soils. There have been limited investigations into its use for reclaiming salt-affected soils. Biochar has the potential to mitigate salt toxicity by working as a soil amendment using organic matter-rich materials.

Biochar production

Pyrolysis, a thermochemical process that can convert fuel into biochar, is a powerful method for producing biochar commercially. Several products are produced from biomass, such as syngas (mainly hydrogen ions, CH_4, and carbon monoxide), bio-oil (alcohols, fats, tars, acids), and biochar (primarily carbon and nitrogen ions, as well as carbon ash) (Vuppaladadiyam et al., 2022). Pyrolysis can be optimized for maximum oil, char, or gas production by adjusting process parameters. According to temperatures and reaction times, pyrolysis techniques can be classified as slow, fast, or gasifying. During pyrolysis (slow heating for moments or seconds) a clean biomass (no oxygen) is transferred into a continuously flowing gas flow (gas flow removing volatile BC emerges at the other end). Fast pyrolysis, however, uses extremely fast heat transfer, typically using too fine biomass particles and rapid heating rates (500–1000^{o}C)

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

(Yashikaa et al., 2020). Biochar derived from leaves has an in-between mineral content, while biochar derived from manure contains a higher level of water-soluble salts, whereas wood-derived biochar contains the highest level of water-soluble salts (Joseph et al., 2021). Approximately 20% of the carbon dioxide in biochar comes from labile carbon dioxide, which mineralizes over time after it is applied to soil, while the remaining 25% is composed of recalcitrant carbon dioxide, which mineralizes over time by both abiotic and biotic processes (Nguyen et al., 2022).

Effects of biochar on soil properties

Soil health and crop production have been threatened by salt contamination in recent decades. It is difficult to develop agriculture on salt-affected soils, because they contain sodium ions (Na^+), lack nutrients, and have altered soil structure. A biochar amendment will generally reduce both the bulk density and particle density of the soil. The addition of biochar to soil improves soil texture and enhances soil aggregates by increasing porosity, reducing bulk density, and reducing particle size (Blanco-Canqui, 2017). By reducing the concentration of Na^+ in soil colloids, biochar reduces the concentration of sodium ions (Ex-Na) in the soil. By exchange of cations with the calcium and magnesium ions, biochar accelerates salt leaching during irrigation (Gao et al., 2024). Biochar releases cations such as potassium, calcium, magnesium, and sodium, causing pH to increase (*Fig. 2*). Due to its longevity in soil, biochar can keep soil pH high for longer periods than other neutralizing materials (Hailegnaw et al., 2019). Since biochar fertilizers are absorbed and disposed of slowly, nutrients are released slowly into the soil, as a result of the absorption-disposal process. In biochar, porous and networked particles prevent nutrients from easily dissolving. With its functional groups that have a high capacity to absorb nutrients, biochar inserts nutrients into the soil's problems to provide a nutrient source for the plants.

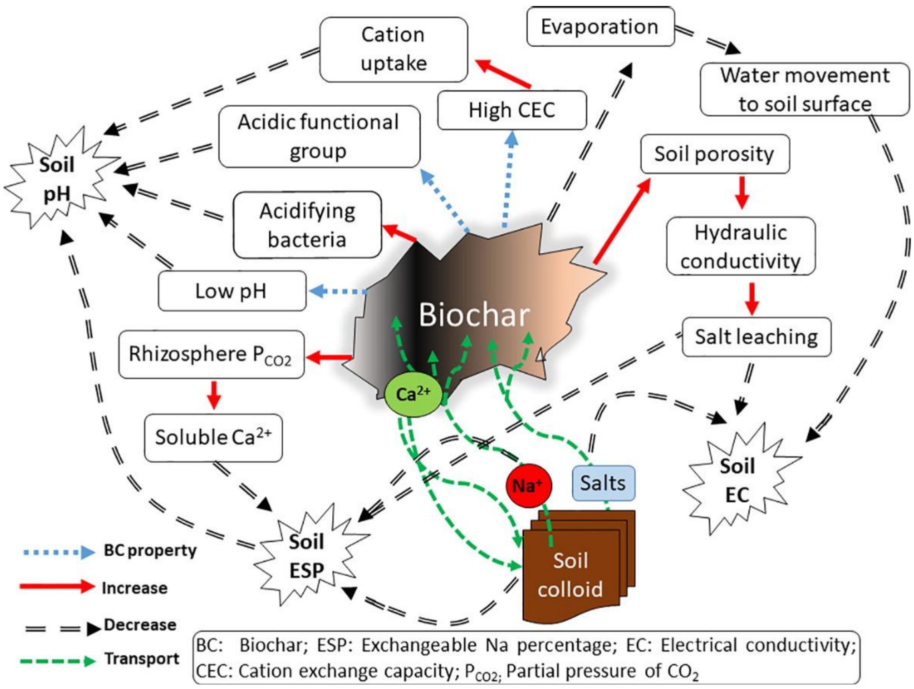

Figure 2. *Effect of biochar on available soil properties (Saifullah et al., 2018)*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

As biochar has a porous structure, microorganisms can grow safely (as mycorrhizal fungi and actinomycetes bacteria) (Yang et al., 2022). Protozoa, mites, nematodes, and other microbes eat these microorganisms in the soil. Additionally, biochar reduces greenhouse gas emissions in soil in addition to maintaining microbiological populations. Earthworm dehydration can be mitigated by applying wet biochar (Li et al., 2021). A boosting of soil enzyme activity, a measure of soil quality, has also been shown by biochar amendments. The use of biochar (charred biomass) as a long-term carbon removal tool is possible due to its recalcitrant nature (Lehmann et al., 2021). Because biochar is capable of storing carbon for up to a century, it plays a major role in soil fertility and carbon sequestration. The mineralization of SOM should have a significant effect on global climate change (Lyu et al., 2021). A priming effect has been suggested by research that says adding biochar to soil can accelerate organic matter decomposition (Cui et al., 2017). Biochar addition to soil stimulated the decomposition of plant residues without causing CO2 to increase (Minamino et al., 2019). In addition to improving soil organic matter (SOM), it may also enhance water retention and soil biological activity (Nepal et al., 2023).

Effect of biochar on soil nutrient dynamics

Among the nutrients found within biochar co-products are nitrogen (N), potassium (K), phosphorus (P), magnesium (Mg), and calcium (Ca) (*Fig. 3*). Cow manure biochar significantly increased N, P, K, Ca, Mg, pH, total C, Olsen-P, exchangeable K, Ca, Mg, and CEC in sandy soil amended with biochar (Uzoma et al., 2011). Combined biochar and nitrogen fertilizer have been shown to be beneficial for soil and plant growth (Laird et al., 2009). Combining nitrogen fertilizer and biochar has been demonstrated to have a significant interaction between biochar and nitrogen. By retaining minerals and fixing them biologically, biochar boosts nitrogen utilization efficiency (Khan et al., 2024). Chan et al. (2007) found that biochar applied with nitrogen fertilizer for radish crops did not improve biomass yield. However, with increasing rates of biochar application and nitrogen fertilizer, the crop's output increased. Biochar does not directly provide nitrogen to crops as conventional fertilizers do, since it is almost entirely composed of recalcitrant aromatic compounds rather than bio-available amines.

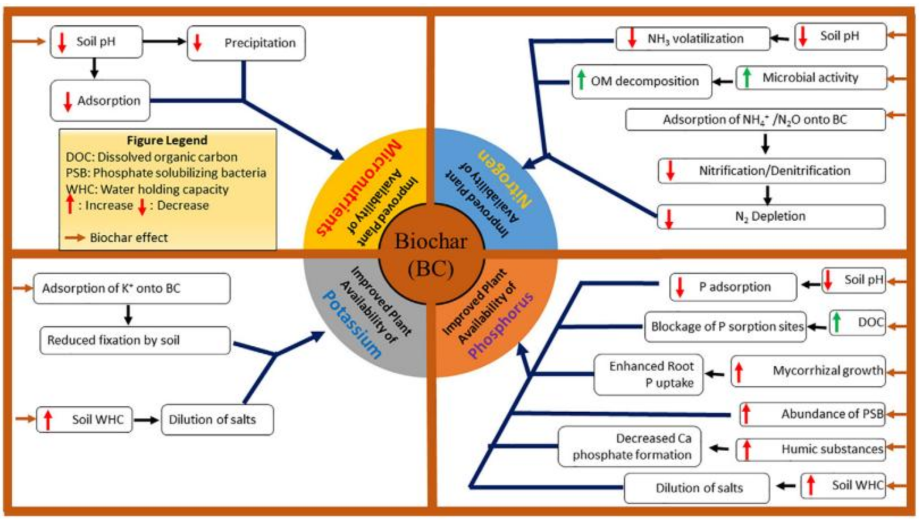

Figure 3. *Effect of biochar on soil nutrient dynamics (Saifullah et al., 2018)*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Reclamation of salt-affected soils with biochar

Numerous studies have investigated the effectiveness of organic amendments and saline-sodic soil reclamation using biochar, dried sludge, farmyard manure, chicken manure, and compost (Chaganti and Crohn, 2015). To increase crop productivity and soil fertility under saline and sodic conditions, biochar can be added to the soil. Carbon sequestration can be achieved through biochar because it recycles wastes, retains soil nutrients, and reduces greenhouse gas emissions (Yadav et al., 2023). It is essential to improve soil quality for agriculture in saline and sodic soil to maximize crop yields and soil fertility (*Fig. 4)*.

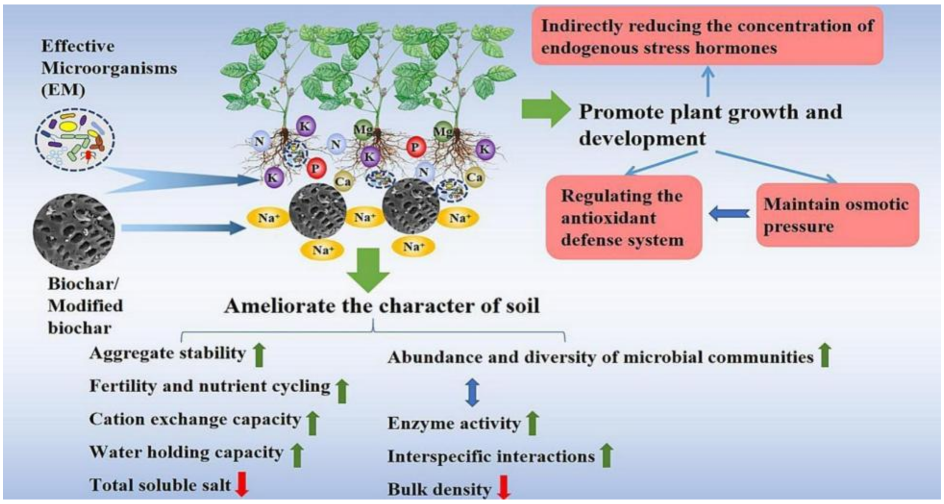

Figure 4. *Influence of biochar on the salt-affected soils (Gao et al., 2024)*

Composted biochar has been associated with several benefits, including improved soil health (*Table 3*). Additionally, biochar was found to enhance soil bulk density, porosity, and aggregate stability (Ul Islam et al., 2021). Water infiltration is facilitated by allowing soil layers to be permeable to water. Biochar has been proven to remove pollutants from contaminated soils and water in a variety of applications. The physicochemical and biological properties of agro-environments are measurable after applying biochar (Das et al., 2023). Biochar applications in agriculture, environment, and energy have increased as a result of food security, environmental pollution, and energy shortage (Chen et al., 2019). To offset Na^+ on exchange sites in saline-sodic soils, basic cations such as Ca^{2+} and Mg^{2+} can be added through biochar. In addition, biochar adsorbs nitrate and reduces salinity stress. The addition of divalent cations can thus reduce salt leaching from saline-sodic soil amended with biochar and improve chemical and physical properties.

Effect of biochar on crops under salt-affected soil

A variety of affordable methods are being studied each year to reduce soil problems (such as those caused by saline, sodic, acidic, alkaline, and pollution stresses). A low-cost way of increasing soil fertility and productivity has been proposed using biochar amendments, although some methods and remediation materials have not been explored yet. Increasing crop yield and improving soil health are both possible benefits of biochar remediation (*Table 4*).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Table 3. *Effect of biochar application on changes in salt-affected soil*

S. No.	Changes in soil properties	References
1.	Increase nutrient absorption capacity and increase nutrient availability	(Nepal et al., 2023)
2.	Improve the soil physical, chemical, and biological properties	(Zhang et al., 2021)
3.	Enhance calcium and magnesium availability	(Antonangelo et al., 2024)
4.	Build-up divalent cation concentrations and nutrient retention	(Hossain et al., 2020; Dey et al., 2023)
5.	Improve cation exchange capacity, nutrient retention capacity, and stable structure	(Sakhiya et al., 2020)
6.	Reduce SAR value and sodicity	(Wang et al., 2023)
7.	Increase soil organic carbon	(Ullah et al., 2018)
8.	Increase soil enzyme and microbial load	(Amoakwah et al., 2022)
9.	Increase soil ion exchange capacity of soil	(Domingues et al., 2020)
10.	Improve bulk density, water holding capacity, soil aeration, hydraulic conductivity, and aggregate stability	(Khan et al., 2024; Wei et al., 2023)
11.	Reduce the salinity stress	(Kul et al., 2021)
12.	Prevent salt sorption by plant	(Murtaza et al., 2024)
13.	Enrich nutrient status and ion sorption capacity	(Ullah et al., 2018)
14.	Biochar application ameliorates the negative effects of drought and salt stress on plants	(Nepal et al., 2023; Zang et al., 2023)
15.	Enhance soil fertility, growth, and development of plant	(Khan et al., 2024)
16.	Increase exchange capacity, and organic carbon, reduce bulk density, and increase porosity	(Singh et al., 2022)
17.	Increase water retention and the micropore/macropore ratio and reduced bulk density	(Tanure et al., 2019)

Challenges and future directions in harnessing biochar benefits in agriculture

A number of factors limit the potential of biochar in agriculture, despite its valuable benefits. The importance of biochar in soil health and agricultural productivity plays a major role. The research should aim to achieve the following requirements in the future.

1. To better manage problem soils with biochar, detailed studies on the long-term potential effects of biochar application are needed.
2. Limited research on the reclamation effect of biochar has been conducted under wide range of soil and climatic conditions. Therefore more researches on a wide range of soil and climatic conditions need to be studied.
3. Biochar is produced from various sources, so it is necessary to study its nature and properties to select the most appropriate source for the suitable problem.
4. A great deal of work needs to be done to calibrate different doses and calculate the correct quantity of product to use on the field.
5. The combined effect of biochar application with other soil amendments needs to be studied to explore the compatibility for adoption.
6. Several researches have been conducted that biochar lowers soil pollution behavior and heavy metal levels in lab conditions. Therefore, extensive research under field condition on the topic is required.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

Table 4. *Influence of biochar on crop growth under salt-affected soil*

S. No.	Crop	Performance	References
1.	Rice	Reduce sodium ion accumulation and increase dry matter production and rice yield (15.81 %)	(Hafez et al., 2021; Jin et al., 2018)
2.	Maize	Increased nutrient uptake and yield	(Mahmoud et al., 2024)
3.	Pearl millet	Increase plant height, leaf area index, and yield	(Rezk Esawy et al., 2017)
4.	Banana	Increase pseudo stem and leaf lengths, leaf area, and bunch, cluster, and finger weights (8.51t/ha)	(Abo-Ogiala, 2018)
5.	Cotton-wheat	Increased cotton yields (12–44%) and wheat grain yields (7–27%) under saline water irrigation.	(Singh et al., 2021)
6.	Cowpea	Improved plant growth characteristics (plant height, dry matter production, yield, and yield attributes)	(Ravi Teja et al., 2022)
7.	Maize	Recorded highest grain yield, grain quality, and stover yield	(Nehela et al., 2021; Wang et al., 2023)
8.	Sorghum	Increased biomass and grain yield by 51.37% and 47.33% respectively	(Zhou et al., 2021)
9.	Soybean	Biochar increased biomass production and seed yield on average by 67% and 54%, respectively	(Fatima et al., 2015)
10.	Sugarcane	Improved cane yield of 128.43t/ha	(Mary and Anitha, 2019)
11.	Tomato	Increased vegetative growth, tomato yield, and quality parameters	(She et al., 2018)
12.	Lettuce and cabbage	Increased lettuce and cabbage biomass yield (90.3%)	(Severoglu et al., 2023)

Conclusion

Global agriculture faces a serious threat of salt-induced soil degradation, which has contributed to the diminished productivity of agroecosystems. Due to the low osmotic potential, ion toxicity, and imbalance of salts in soil, high salt concentrations inhibit plant growth and reduce crop yields. Salt toxicity and excess soluble salts are not the only reasons for low productivity in saline soils, but also the lack of mineral nutrients, especially nitrogen, phosphorus, potassium, and soil organic matter. Hence, preserving salt-affected soils is of paramount importance to meet the needs of an ever-increasing population. Biochar can alter nutrient dynamics, soil contaminants, and microbial functions in soil by altering nutrient dynamics. Therefore, applying biochar strategically to soil may provide agronomic, environmental, and economic benefits. Biochar amendments are not only effective but also affordable ways to improve salt-affected soils' physical, chemical, and biological properties and productivity in salinity-affected soils. With its strong adsorption, biochar reduces the sodium concentrations in soil colloids, or it exchanges sodium ions on its surface. Plants absorbed less sodium when exposed to salt stress, while they absorbed more potassium when exposed to salt stress. In addition to enhancing water retention and nutrient absorption, it also promotes microbial activity, leading to the development of a fertile environment for agriculture that is sustainable and resilient. Moreover, biochar serves as a carbon sink, which mitigates the impacts of climate change by storing carbon long-term.

Conflicts of interest. The authors declare no conflict of interest.

REFERENCES

[1] Abdul Rahman, N. S. N., Abdul Hamid. N. W., Nadarajah. K. (2021): Effects of Abiotic Stress on soil microbiome. – International Journal of Molecular Sciences 2216: 9036. https://doi: 10.3390/ijms22169036. PMID: 34445742; PMCID: PMC8396473.

[2] Abo-Ogiala, A. M. (2018): Impact of biochar on vegetative parameters, leaf mineral content, yield and fruit quality of grande naine banana in saline-sodic soil. – Egypt. J. Hort. 452: 315-322.

[3] Al Hinai, M. S., Ullah, A., Al-Rajhi, R. S., Farooq, M. (2022): Proline accumulation, ion homeostasis and antioxidant defence system alleviate salt stress and protect carbon assimilation in bread wheat genotypes of Omani origin. – Environmental and Experimental Botany 193: 104687.

[4] Al-Rumaihi, A., Shahbaz, M., McKay, G., Mackey, H., Al-Ansari, T. (2022): A review of pyrolysis technologies and feedstock: A blending approach for plastic and biomass towards optimum biochar yield. – Renewable and Sustainable Energy Reviews 176: 112715. https://doi.org/10.1016/j.rser.2022.112715.

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

[6] Amoakwah, E., Arthur, E., Frimpong, K. A., Lorenz, N., Rahman, A. M., Nziguheba, G., Islam, R. (2022): Biochar amendment impacts on microbial community structures and biological and enzyme activities in a weathered tropical sandy loam. – Applied Soil Ecology 172: 104364. ISSN 0929-1393. https://doi.org/10.1016/j.apsoil.2021.104364.

[7] Antonangelo, J. A., Culman, S., Zhang, H. (2024): Comparative analysis and prediction of cation exchange capacity via summation: influence of biochar type and nutrient ratios. – Front. Soil Sci. 4: 1371777. Doi: 10.3389/fsoil.2024.1371777.

[8] Atta, K., Mondal, S., Gorai, S., Singh, A. P., Kumari, A., Ghosh, T., Roy, A., Hembram, S., Gaikwad, D. J., Mondal, S., Bhattacharya, S., Jha, U. C., Jespersen, D. (2023): Impacts of salinity stress on crop plants: improving salt tolerance through genetic and molecular dissection. – Front. Plant Sci. 15: 1241736. Doi: 10.3389/fpls.2023.1241736. PMID: 37780527; PMCID: PMC10540871.

[9] Bernstein, N. (2019): Plants and salt: Plant response and adaptations to salinity. – In Astrobiology Exploring Life on Earth and Beyond, Model Ecosystems in Extreme Environments, Academic Press, pp. 101-112. ISBN 9780128127421, https://doi.org/10.1016/B978-0-12-812742-1.00005-2.

[10] Bhattacharyya, R., Ghosh, B. N., Dogra, P. P. K., Mishra Santra, P., Kumar, S., Fullen, M. A., Mandal, U. K., Anil, K. S., Lalitha, M., Sarkar, S. (2016): Soil conservation issues in India. – Sust. 8: 565.

[11] Bidalia, A., Vikram, K., Yamal, G., Rao, K. S. (2019): Effect of salinity on soil nutrients and plant health. – In: Akhtar, M. (ed.) Salt Stress, Microbes, and Plant Interactions: Causes and Solution. Springer, Singapore. https://doi.org/10.1007/978-981-13-8801-9_13.

[12] Blanco-Canqui, H. (2017): Biochar and soil physical properties. – Soil Science Society of America Journal 81: 687-711. https://doi.org/10.2136/sssaj2017.01.0017.

[13] Chaganti, V. N., Crohn, D. M. (2015): Evaluating the relative contribution of physiochemical and biological factors in ameliorating a saline–sodic soil amended with composts and biochar and leached with reclaimed water. – Geoderma 259: 45-55.

[14] Chahal, S. S., Choudhary, O. P., Mavi, M. S. (2017): Organic amendments decomposability influences microbial activity in saline soils. – Arch. Agron. Soil Sci. 1: 1-4.

[15] Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S. (2007): Agronomic values of green waste biochar as a soil amendment. – Australian Journal of Soil Research 45: 629-634. 10.1071/SR07109.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

[16] Chaves, M. M., Flexas, J., Pinheiro, C. (2009): Photosynthesis under drought and salt stress: regulation mechanisms from whole plant to cell. – Ann Bot. 103: 551-560.
[17] Chen, Y., Chen, S., Li, K., Zhang, Y., Huang, X., Li, T., Wu, S., Wang, Y., Carey, L. B., Qian, W. (2019): Over dosage of balanced protein complexes reduces proliferation rate in aneuploid cells. – Cell Systems 92: 129-142.
[18] Cui, N., Hu, M., Khalil, R. A. (2017): Biochemical and biological attributes of *Matrix metalloproteinases*. – Prog. Mol. Biol. Transl. Sci. 147: 1-73. Doi: 10.1016/bs.pmbts.2017.02.005.
[19] Cui, J., Ge, T., Kuzyakov, Y., Nie, M., Fang, C., Tang, B., Zhou, C. (2017): Interactions between biochar and litter priming: A three-source 14 C and 13 C partitioning study. – Soil Biol. Biochem. 104: 49-58.
[20] Dang, D. M., Macdonald, B., Warneke, S., White, I. (2017): Available carbon and nitrate increase greenhouse gas emissions from soils affected by salinity. – Soil Res. 55: 47-57.
[21] Das, S. K., Ghosh, G. K., Avasthe, R. (2023): Application of biochar in agriculture and environment, and its safety issues. – Biomass Conv. Bioref. 13: 1359-1369. https://doi.org/10.1007/s13399-020-01013-4.
[22] Dey, S., Purakayastha, T. J., Sarkar, B., Rinklebe, J., Kumar, S., Chakraborty, R., Datta, A., Lal, K., Shivay, Y. S. (2023): Enhancing cation and anion exchange capacity of rice straw biochar by chemical modification for increased plant nutrient retention. – Science of The Total Environment 886: 163681. ISSN 0048-9697,https://doi.org/10.1016/j.scitotenv.2023.163681.
[23] Domingues, R. R., Sánchez-Monedero, M. A., Spokas, K. A., Melo, L. C. A., Trugilho, P. F., Valenciano, M. N., Silva, C. A. (2020): Enhancing cation exchange capacity of weathered soils using biochar: feedstock, pyrolysis conditions and addition rate. – Agronomy 106: 824. https://doi.org/10.3390/agronomy10060824.
[24] Dourado, P. R. M., Souza, E., dos Santos, M. A., Lins, C. M. T., Monteiro, D. R., Paulino, M., Schaffer, B. (2022): Stomatal regulation and osmotic adjustment in sorghum in response to salinity. – Agriculture 125: 658.
[25] Egamberdieva, D., Davranov, K., Wirth, S. (2018): Soil salinity and microbes: diversity, ecology, and biotechnological potential. – In: Egamberdieva, D., Birkeland, N. K., Panosyan, H., Li, W. J. (eds.) Extremophiles in Eurasian Ecosystems: Ecology, Diversity, and Applications. Microorganisms for Sustainability. – Springer 8. https://doi.org/10.1007/978-981-13-0329-6_11.
[26] Ehtaiwesh, A., Rashed, F. (2019): The effect of salinity on Libyan soft wheat *Triticum aestivum* L. at germination stage. – Journal of Applied Science 32: 41-54.
[27] Ehtaiwesh, A. F. (2022): The effect of salinity on nutrient availability and uptake in crop plants. – Journal of Applied Science 9: 55-73.
[28] Elmeknassi, M., Elghali, A., de Carvalho, H. W. P., Laamrani, A., Benzaazoua, M. (2024): A review of organic and inorganic amendments to treat saline-sodic soils: Emphasis on waste valorization for a circular economy approach. – Science of The Total Environment 921: 171087. ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2024.171087.
[29] Emrich, W. (1985): Handbook of Charcoal Making: The Traditional and Industrial Methods. – D. Reidel Publishing Company, pp. 232-235
[30] Fatima, Y., Doi, S. A., Mamun, A. A. (2015): Longitudinal impact of sleep on overweight and obesity in children and adolescents: a systematic review and bias-adjusted meta-analysis. – Obes. Rev. 162: 137-149. doi: 10.1111/obr.12245. Epub 2015 Jan 14. PMID: 25589359.
[31] Fedeli, R., Vannini, A., Djatouf, N. S., Celletti Loppi, S. (2024): Can lettuce plants grow in saline soils supplemented with biochar. – Heliyon 10(4): e26526. doi: 10.1016/j.heliyon.2024.e26526. PMID: 38404867; PMCID: PMC10884517.
[32] Gao, G., Yan, L., Tong, K., Yu, H., Lu, M., Wang, L., Niu, Y. (2024): The potential and prospects of modified biochar for comprehensive management of salt-affected soils and

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2301_749767

plants: A critical review. – Sci. Total Environ. 20(12): 169618. doi: 10.1016/j.scitotenv.2023.169618. Epub 2023 Dec 27. PMID: 38157902.
[33] Giuffrida, F., Scuderi, D., Giurato, R., Leonardi, C. (2013): Physiological response of broccoli and cauliflower as affected by NaCl salinity. – Acta Horticulturae 1005: 435-441.
[34] Hafez, E. M., Gowayed, S. M., Nehela, Y., Sakran, R. M., Rady, A. M. S., Awadalla, A., El-Dein Omara, A., Alowaiesh, B. F. (2021): Incorporated biochar-based soil amendment and exogenous glycine betaine foliar application ameliorate rice *Oryza sativa* L. Tolerance and Resilience to Osmotic Stress. – Plants 10: 1930. 10.3390/plants10091930.
[35] Hailegnaw, N. S., Mercl, F., Pračke, K. (2019): Mutual relationships of biochar and soil pH, CEC, and exchangeable b se cations in a model laboratory experiment. – J Soils Sediments 19: 2405-2416.https://doi.org/10.1007/s11368-019-02264-z.
[36] Hassani, A., Smith, P., Shokri, N. (2024): Negative correlation between soil salinity and soil organic carbon variability. – Earth, Atmospheric, and Planetary Sciences 1218: e2317332121.
[37] Hazman, M., Hause, B., Eiche, E., Riemann, M., Nick, P. (2016): Different forms of osmotic stress evoke qualitatively different responses in rice. – Journal of Plant Physiology 202: 45-56.
[38] Hopmans, J. W., Qureshi, A. S., Kisekka, I., Munns, R., Grattan, S. R., Rengasamy, P., Ben-Gal, A., Assouline, S., Javaux, M., Minhas, P. S., Raats, P. A. C., Skaggs, T. H., Wang, G., De Jong van Lier, Q., Jiao, H., Lavado, R. S., Lazarovitch, N., Li, B., Taleisnik, E. (2021): Critical knowledge gaps and research priorities in global soil salinity. – In: Sparks, D. L. (ed.) Advances in Agronomy. Chapter One, Academic Press 169: 1-191.
[39] Hossain, Z., Bahar, M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., Bolan, N. (2020): Biochar and its importance on nutrient dynamics in soil and plant. – Biochar 2: 379-420. 10.1007/s42773-020-00065-z.
[40] Iwasaki, T., Suzuki, S., Kojima, T. (2014): Influence of Biomass Pyrolysis Temperature, Heating Rate and Type of Biomass on Produced Char in a Fluidized Bed Reactor. – Energy and Environment Research 4. 10.5539/eer.v4n2p64.
[41] Jin, F., Ran, C., Anwari, Q., Geng, Y., Guo, L., Li, J., Han, D., Zhang, X., Liu, X., Shao, X. (2018): Effects of biochar on sodium ion accumulation, yield and quality of rice in saline-sodic soil of the west of Songnen plain, northeast China. – Plant, Soil and Environment 64: 612-618.
[42] Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Ok, Y. S., Palansooriya, K. N., 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: 1731-1764. https://doi.org/10.1111/gcbb.12885.
[43] Khan, S., Irshad, S., Mehmood, K., Hasnain, Z., Nawaz, M., Rais, A., Gul, S., Wahid, M. A., Hashem, A., Abd Allah, E. F., Ibrar, D. (2024): Biochar production and characteristics, its impacts on soil health, crop production, and yield enhancement: A Review. – Plants Basel 132: 166. doi: 10.3390/plants13020166. PMID: 38256720; PMCID: PMC10821463.
[44] Kul, R., Arjumend, T., Ekinci, M., Yildirim, E., Turan, M., Argin, S. (2021): Biochar as an organic soil conditioner for mitigating salinity stress in tomato. – Soil Science and Plant Nutrition 676: 693-706. https://doi.org/10.1080/00380768.2021.1998924.
[45] Laird, D. A., Brown, R. C., Amonette, J. E., Lehmann, J. (2009): Review of the pyrolysis platform for coproducing bio-oil and biochar. – Biofuels Bio-product Biorefining 3: 547-562.
[46] Lehmann, J., Bossio, D. A., Kögel-Knabner, I., Rillig, M. C. (2020): The concept and future prospects of soil health. – Nat. Rev. Earth Environ. 1(10): 544-553. doi:

10.1038/s43017-020-0080-8. Epub 2020 Aug 25. PMID: 33015639; PMCID: PMC7116140.
[47] Lehmann, J., Cowie, A., Masiello, C. A. (2021): Biochar in climate change mitigation. – Nat. Geosci. 14: 883-892. https://doi.org/10.1038/s41561-021-00852-8.
[48] Li, X., Wang, A., Wan, W., Luo, X., Zheng, L., He, G., Huang, D., Chen, W., Haung, Q. (2021): High Salinity Inhibits Soil Bacterial Community Mediating Nitrogen Cycling. – Appl. Environ. Microbiol. 87(21): e0136621. doi: 10.1128/AEM.01366-21. PMID: 34406835; PMCID: PMC8516042.
[49] Lu, Y., Fricke, W. (2023): Salt stress-regulation of root water uptake in a whole-plant and diurnal context. – Int. J. Mol. Sci. 29(249): 8070. doi: 10.3390/ijms24098070. PMID: 37175779; PMCID: PMC10179082.
[50] Lyu, H., Watanabe, T., Kilasara, M., Hartono, A., Funakawa, S. (2021): Soil organic carbon pools controlled by climate and geochemistry in tropical volcanic regions. – Science of the Total Environment 761: 143277. https://doi.org/10.1016/j.scitotenv.2020.143277.
[51] Mahmoud, E., El Baroudy, A. A., Abd El-Kader, N. K., Othman, S., El Khamisy, R. (2017): Effects of phosphogypsum and biochar addition on soil physical properties and nutrients uptake by maize yield in Vertic Torrifluvents. – International Journal of Scientific & Engineering Research 8 (8).
[52] Mahmoud, E., El-Shahawy, A., Ibrahim, M., Abd El-Halim A., Abo-Ogiala, A., Shokr, M. S., Mohamed, E. S., Rebouh, N. Y., Ismail, S. M. (2024): Enhancing maize yield and soil health through the residual impact of nanomaterials in contaminated soils to sustain food. – Nanomaterials 14(4): 369. https://doi.org/10.3390/nano14040369.
[53] Mary, P. C. N., Anitha, R. (2019): Effect of sugarcane trash biochar on enhancement of soil health and sugarcane productivity. – Int. J. Curr. Microbiol. App. Sci. 811: 2650-2660. doi: https://doi.org/10.20546/ijcmas.2019.811.304.
[54] Melgar, S., Karlsson, L., Rehnström, E., Karlsson, A., Utkovic, H., Jansson, L., Michaëlsson, E. (2008): Validation of murine dextran sulfate sodium-induced colitis using four therapeutic agents for human inflammatory bowel disease. – Int. Immuno. pharmacol. 86: 836-844. doi: 10.1016/j.intimp.2008.01.036. Epub 2008 Mar 7. PMID: 18442787.
[55] Minamino, Y., Fujitake, N., Suzuki, T., Yoshitake, S., Koizumi, H., Tomotsune, M. (2019): Effect of biochar addition on leaf-litter decomposition at soil surface during three years in a warm-temperate secondary deciduous forest. – Japan. Sci. Rep. 91: 16961. doi: 10.1038/s41598-019-53615-2. PMID: 31740758; PMCID: PMC6861223.
[56] Mohammad Khani, N., Heidari, R., Abbaspour, N., Rahmani, F. (2018): Effects of salinity on plant hormones genes in grape. – Iranian Journal of Science and Technology, Transactions A: Science 422: 401-410.
[57] Mohanavelu, A., Naganna, S. R., Al-Ansari, N. (2021): Irrigation induced salinity and sodicity hazards on soil and groundwater: an overview of its causes, impacts and mitigation strategies. – Agriculture 1110: 983. https://doi.org/10.3390/agriculture11100983.
[58] Muhammad, M., Waheed, A., Wahab, A., Majeed, M., Nazim, M., Liu, Y. H., Li, L., Li, W. J. (2023): Soil salinity and drought tolerance: An evaluation of plant growth, productivity, microbial diversity, and amelioration strategies. – Plant Stress 11: 100319. ISSN 2667-064X,https://doi.org/10.1016/j.stress.2023.100319.
[59] Munns, R., Gilliham, M. (2015): Salinity tolerance of crops - what is the cost? – New Phytol. 2083: 668-673. doi: 10.1111/nph.13519. Epub 2015 Jun 24. PMID: 26108441.
[60] Murtaza, G., Rizwan, M., Usman, M., Hyder, S., Akram, M. I., Deeb, M., Alkahtani, J., Al Munqedhi, B. M., Hendy, A. S., Ali, M. R., Iqbal, R., Harsonowati, W., Habib Ur Rahman, M., Rizwan, M. (2024): Biochar enhances the growth and physiological characteristics of *Medicago sativa*, *Amaranthus caudatus* and *Zea mays* in saline soils. –

BMC Plant Biol. 241: 304. doi: 10.1186/s12870-024-04957-1. PMID: 38644487; PMCID: PMC11034111.
[61] Negacz, K., Malek,Ž., de Vos, A., Vellinga, P. (2022): Saline soils worldwide: Identifying the most promising areas for saline agriculture. – Journal of Arid Environments 203: 104775. ISSN 0140-1963. https://doi.org/10.1016/j.jaridenv.2022.104775.
[62] Nehela, Y., Mazrou, Y. S. A., Alshaal, T., Rady, A. M. S., El-Sherif, A. M. A., Omara, A. E., Abd El-Mone, A. M., Hafez, E. M. (2021): The integrated amendment of sodic-saline soils using biochar and plant growth-promoting rhizobacteria enhances maize *Zea mays* L. resilience to water salinity. – Plants 10: 1960. https://doi.org/ 10.3390/plants10091960.
[63] Nepal, J., Wiqar, A., Fazal, M., Khan, A., Zou, Z. (2023): Advances and prospects of biochar in improving soil fertility, biochemical quality, and environmental applications. – Frontiers in Environmental Science 11: 14752. https://www.frontiersin.org/articles/10.3389/fenvs.2023.1114752.10.3389/fenvs.2023.
[64] Nguyen, B. T., Dinh, G. D., Nguyen, T. X. (2022): The potential of biochar to ameliorate the major constraints of acidic and salt-affected soils. – J. Soil Sci. Plant Nutr. 22: 1340-1350. https://doi.org/10.1007/s42729-021-00736-1.
[65] Nguyen, T. B., Sherpa, K., Bui, X. T., Nguyen, V. T., Vo, T. D. H., Ho, H. T. T., Chen, C. W., Dong, C. D. (2023): Biochar for soil remediation: A comprehensive review of current research on pollutant removal. – Environmental Pollution 33: 122571. ISSN 0269-7491, https://doi.org/10.1016/j.envpol.2023.122571.
[66] Qadir, M., Quillérou, E., Nangia, V., Murtaza, G., Singh, M., Thomas, R. J., Drechsel, P., Noble, A. D. (2014): Economics of salt-induced land degradation and restoration. – Nat. Resour. Forum 38: 282-295. https://doi.org/10.1111/1477-8947.12054.
[67] Qadir, M., Schubert, S., Ghafoor, A., Murtaza, G. (2001): Amelioration strategies for sodic soils: a review. – Land Degrad. Dev. 12: 357-386. https://doi.org/10.1002/ldr.458.
[68] Ravi Teja, T., Alagesan, A., Avudaithai, S., Ejilane, J., Paul Sebastian, S. (2022): Growth and yield response of cowpea *Vigna unguiculata* L. in sodic soil amended with marine gypsum, biochar and bioinoculants. – Eco. Env. and Cons. 28: S559-S564.
[69] Rengasamy, P., de Lacerda, C. F., Gheyi, H. R. (2022): Salinity, sodicity and alkalinity. – In: de Oliveira, T. S., Bell, R. W. (eds.) Subsoil Constraints for Crop Production. Springer, Cham. https://doi.org/10.1007/978-3-031-00317-2_4.
[70] Saifullah, Dahlawi, S., Naeem, A., Rengel Z., Naidu, R. (2018): Biochar application for the remediation of salt-affected soils: challenges and opportunities. – Sci. Total Environ. 625: 320-335. https://doi: 10.1016/j.scitotenv.2017.12.257. Epub 2017 Dec 28. PMID: 29289780.
[71] Sakhiya, A. K., Anand, A., Kaushal, P. (2020): Production, activation, and applications of biochar in recent times. – Biochar 2: 253-285. https://doi.org/10.1007/s42773-020-00047-1.
[72] Severoğlu, S., Yildirim, E., Ekinci, M., Güllap, M. K., Karabacak, T., Yazici, A., Aktaş, H., Çerit, N. (2023): The Effect of biochar applications at different doses on soybean seedlings grown in salty conditions. – Turkish Journal of Range and Forage Science 41: 38-42.
[73] Shah, S. H., Islam, S., Mohammad, F. (2023): Gibberellic Acid: A versatile regulator of plant growth, development and stress responses. – J. Plant Growth Regul. 42: 7352-7373. https://doi.org/10.1007/s00344-023-11035-7.
[74] Shaygan, M., Baumgartl, T. (2022): Reclamation of salt-affected land: A Review. – Soil Systems 6(3): 61. https://doi.org/10.3390/soilsystems6030061.
[75] She, D., Sun, X., Gamareldawla, A. H. D., Nazar, E. A., Hu, W., Khaembah, E., Yu, S. (2018): Benefits of soil biochar amendments to tomato growth under saline water irrigation. – Scientific Reports 8: 14743. DOI:10.1038/s41598-018-33040-7.

[76] 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 Journal of Biological Sciences. Elsevier B.V. https://doi.org/10.1016/j.sjbs.2014.12.001.
[77] Singh, R., Mavi, M. S., Choudhary, O. P. (2019): Saline soils can be ameliorated by adding biochar generated from rice-residue waste. – Clean Soil, Air and Water 47: 1700656. https://doi.org/10.1002/clen.201700656.
[78] Singh, A. (2021): Soil salinization management for sustainable development: A review. – Journal of Environmental Management 277: 111383. ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2020.111383.
[79] Singh, G., Mavi, M. S., Choudhary, O. P., Gupta, N., Singh, Y. (2021): Rice straw biochar application to soil irrigated with saline water in a cotton-wheat system improves crop performance and soil functionality in north-west India. – Journal of Environmental Management 295: 113277.
[80] Singh, H., Northup, B. K., Rice, C. W. (2022): Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis. – Biochar 4: 8. https://doi.org/10.1007/s42773-022-00138-1.
[81] Stavi, I., Thevs, N., Priori, S. (2021): Soil Salinity and Sodicity in Drylands: A Review of Causes, Effects, Monitoring, and Restoration Measures. – Frontiers in Environmental Science 9. URL=https://www.frontiersin.org/journals/environmental-science/articles/10.3389/fenvs.2021.712831. DOI=10.3389/fenvs.2021.712831.
[82] Tang, H., Du, L., Xia, C., Luo, J. (2024): Bridging gaps and seeding futures: A synthesis of soil salinization and the role of plant-soil interactions under climate change. – iScience 27(9): 110804. ISSN 2589-0042, https://doi.org/10.1016/j.isci.2024.110804.
[83] Tanure, M. M. C., da Costa, L. M., Huiz, H. A., Alves Fernandes, R. B., Cecon, P. R., Pereira Jr, J. D., da Luz, J. M. R. (2019): Soil water retention, physiological characteristics, and growth of maize plants in response to biochar application to soil. – Soil and Tillage Research 192: 164-173. https://doi.org/10.1016/j.still.2019.05.007.
[84] Tarolli, P., Luo, J., Park, E., Barcaccia, G. R. (2024): Soil salinization in agriculture: Mitigation and adaptation strategies combining nature-based solutions and bioengineering. – iScience 27: 108830. 10.1016/j.isci.2024.108830.
[85] Ul Islam, M., Jiang, F., Guo, Z., Peng, X. (2021): Does biochar application improve soil aggregation? A meta-analysis. – Soil and Tillage Research 209: 104926. https://doi.org/10.1016/j.still.2020.104926.
[86] Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E. (2011): Effect of cow manure biochar on maize productivity under sandy soil condition. – Soil Use and Management 27: 205-212. 10.1111/j.1475-2743.2011.00340.
[87] Vaishnavi, A., Singh, J., Singh, P., Rajput, R. S., Singh, H. B., Sarma, B. K. (2024): *Sphingo bacterium* sp. BHU-AV3 induces salt tolerance in tomato by enhancing antioxidant activities and energy metabolism. – Frontiers in Microbiology 272: 108830. ISSN 2589-0042. https://doi.org/10.1016/j.isci.2024.108830.
[88] Vuppaladadiyam, A. K., Vuppaladadiyam, S. S. V., Awasthi, A., Sahoo, A., Rehman, S., Pant, K. K., Murugavelh, S., Huang, Q., Anthony, E., Fennel, P., Bhattacharya, S., Leu, S. Y. (2022): Biomass pyrolysis: A review on recent advancements and green hydrogen production. – Bioresource Technology 364: 128087. https://doi.org/10.1016/j.biortech.2022.128087.
[89] Wang, P., Liu, Q., Fan, S., Wang, J., Mu, S., Zhu, C. (2023): Combined Application of Desulfurization Gypsum and Biochar for Improving Saline-Alkali Soils: A Strategy to Improve Newly Reclaimed Cropland in Coastal Mudflats. – Land 129: 1717. https://doi.org/10.3390/land12091717.
[90] Wang, X., Ding, J., Wang, J., Han, L., Tan, J., Ge, X. (2024): Ameliorating saline-sodic soils: A global meta-analysis of field studies on the influence of exogenous amendments on crop yield. – Land Degradation and Development 35(10): 3330-3343. https://doi.org/10.1002/ldr.5133.

[91] Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., Wang, Z. (2023): Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. – Geoderma 437: 116591. Doi.org/10.1016/j.geoderma.
[92] Wong, V. N. L., Greene, R. S. B., Dalal, R. C., Murphy, B. W. (2010): Soil carbon dynamics in saline and sodic soils: a review. – Soil Use and Management 26: 2-11. https://doi.org/10.1111/j.1475-2743.2009.00251.x.
[93] Wu, H., Zeng, G., Liang, J., Guo, S., Dai, J., Lu, L., Wei, Z., Xu, P., Li, F., Yuan, Y., He, X. (2015): Effect of early dry season induced by the three gorges dam on the soil microbial biomass and bacterial community structure in the Dongting Lake wetland. – Ecological Indicators 53: 129-136.
[94] Yaashikaa, P. R., Senthil Kumar, P., Varjani, S., Saravanan, A. (2020): A critical review on the biochar production techniques, characterization, stability and applications for circular bioeconomy. – Biotechnology Reports 28: e00570. ISSN 2215-017X. https://doi.org/10.1016/j.btre.2020.e00570.
[95] Yadav, S. P. S., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., Ghimire, N., Paudel, P., Paudel, P., Shrestha, J., Oli, B. (2023): Biochar application: A sustainable approach to improve soil health. – Journal of Agriculture and Food Research 11: 100498. ISSN 2666-1543, https://doi.org/10.1016/j.jafr.2023.100498.
[96] Yang, C., Liu, J., Ying, H., Lu, S. (2022): Soil pore structure changes induced y biochar affect microbial diversity and community structure in an *Ultisol*. – Soil and Tillage Research 224: 105505. Doi.org/10.1016/j.still.2022.105505.
[97] Yasuor, H., Yermiyahu, U., Ben-Gal, A. (2020): Consequences of irrigation and fertigation of vegetable crops with variable quality water: Israel as a case study. – Agricultural Water Management 242: 106362. ISSN 0378-3774.https://doi.org/10.1016/j.agwat.2020.106362.
[98] Zhan, C., Wan, D., Han, Y., Zhang, J. (2019): Historical variation of black carbon and PAHs over the last ~200 years in central North China: Evidence from lake sediment records. – Science of the Total Environment 690: 891-899. https://doi.org/10.1016/j.scitotenv.2019.07.008.
[99] Zhang, W.-W., Wang, C., Xue, R., Wang, L.-J. (2019): Effects of salinity on the soil microbial community and soil fertility. – Journal of Integrative Agriculture 186: 1360-1368.
[100] Zhang, Y., Wang, J., Feng, Y. (2021): The effects of biochar addition on soil physicochemical properties: A review. – CATENA 2: 105284. https://doi.org/10.1016/j.catena.2021.105284.
[101] Zhang, W., Wei, J., Guo, L., Fang, H., Liu, X., Liang, K., Niu, W., Liu, F., Siddique, K. H. M. (2023): Effects of two biochar types on mitigating drought and salt stress in tomato seedlings. – Agronomy 13(4): 1039. https://doi.org/10.3390/agronomy13041039.
[102] Zhang, G., Bai, J., Zhai, Y., Jia, J., Zhao, Q., Wang, W., Hu, X. (2024): Microbial diversity and functions in saline soils: A review from a biogeochemical perspective. – Journal of Advanced Research 59: 129-140. ISSN 2090-1232. https://doi.org/10.1016/j.jare.2023.06.015.
[103] Zhou, Z., Li, Z., Zhang, Z., You, L., Xu, L., Huang, H., Wang, X., Gao, Y., Cui, X. (2021): Treatment of the saline-alkali soil with acidic corn stalk biochar and its effect on the sorghum yield in western Songnen Plain. – Science of the Total Environment 797: 149190.