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REVIEW

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Overview of biochar role in remediating soil salinity stress in crops

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Abstract

Salt stress has been a major problem in the soils of the world. Semi-arid and arid soils are the most affected and bring about adverse crop productivity and yield especially in susceptible species. Salinity is usually denoted with electrical conductivity (EC) equal to or greater than 4 deci Siemens per meter (dS/m). With expanding areas affected by salinity, especially with increasing sea water level and incursion of land, rise in salty water table is eminent as consequences of climate change. Sustainable remediation of soil salinity is becoming a major concern, especially in the field of agriculture and climate change mitigation. Remediation of saline soil with application of organic amendments has shown positive results with the added advantage of carbon build up in the soil. Recently with the focus on biochar as one of the recent soil conditioners and amendment, many researchers have tried to find out its remediating capacity on soil salinity. This article will focus on how biochar affects soil salinity with much emphasis on cation exchange capacity (CEC) and anion exchange capacity (AEC). Results from researchers showed that biochar remediates soil salinity due to its inherent characteristics like high CEC and possession of AEC that deprives both cations and anions that form salt in the soil. This positively favour the thrival of crops under salt stress by boosting K^+ availability, high salt sorption capacity, increased plant water intake, accelerated transpiration, lowered soil EC, increased soil accessible nutrients, increased soil moisture saving, optimizes the water-salt balance of the soil during saline irrigation, extended life span of plant which all favour crop performance. Future studies should explore synergistic effects of combining biochar with other soil management practices like drainage systems to enhance salinity mitigation and crop performance. Additionally, nano-biochar represents a promising direction in biochar development, with more possible potential for salinity amelioration due to higher surface area compared to biochar. While biochar has the potential to mitigate this issue, research on its application in African contexts is limited. More localized studies are needed to develop effective biochar solutions tailored to specific African environments and agricultural practices.

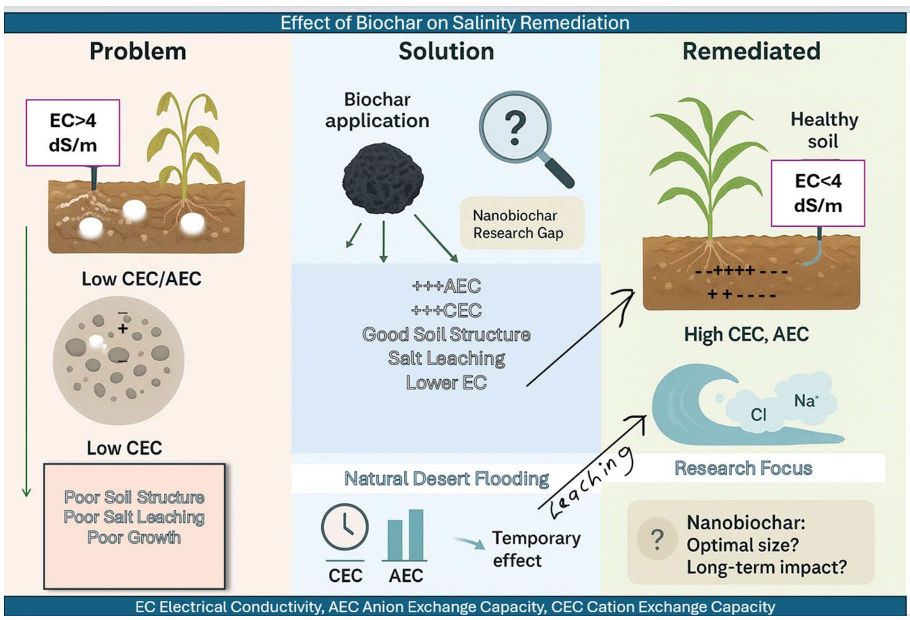
Article highlights

- Biochar is much promising for ameliorating soil salinity.
- Biochar had CEC and AEC, reducing the impact of soil salinity.

- Localized studies are essential to understand biochar's effectiveness in ameliorating soil salinity, given the high variability of soil conditions.

Keywords Anion exchange capacity, Biochar, Cations, Cation exchange capacity, Electrical conductivity, Crops, Salinity

Graphical abstract



1 Introduction

According to Zaman et al. [249], soil salinity is expressed by the concentration of different salts dissolved within the profile of that soil. Those salts that dissolve in water more than gypsum are referred to as soluble salts and are used in delineating saline soils [118]. Electrical conductivity (EC) has proved to be a reliable method of assessing the degree of soil salinity since it measures the amount of soluble salts in water extracted from the soil. The EC of the extract from a soil sample prepared by saturating a paste of the soil corresponding to or exceeding 4 deci Siemens per meter (dS/m) per unit area at 25 °C is regarded as saline. One natural factor that has raised considerable concern in agricultural production is soil salinity which mainly affects arid and semi-arid areas of the world. These adverse effects raise more concern on the inherent properties of the soil and plant physiological processes [177].

Soil salinity affects agricultural production in a significant way, making it a huge problem for the agricultural industry to feed the ever-increasing world population [122]. Similarly, Suhani et al. [209] have highlighted that salinity is developed through high water table, over-irrigation, floods, sedimentation, and leakage. It was reported that salinity has a significant impact on crop yield reduction with respect to plant physiology and biochemical factors [119]. The presence of high salt concentrations creates osmotic stress that prevents plants from absorbing water from their soil environment. Plants experience dehydration along with growth reduction because salinity leads to diminished water availability in their cells [5, 116, 238]. The high level of Na^+ and Cl^- salts that accumulate within plant tissues induce toxic effects that disrupt cell functions, damaging membranes and blocking enzyme processes and ultimately impair plant development

[2, 116, 184]. Moreover, salinity interferes with the uptake of essential nutrients. Plants experience nutrient deficiencies from K^+ absorption inhibition caused by high Na^+ levels, which ultimately damages metabolic functions and physiological processes [2, 116]. The presence of saline conditions activates the formation of reactive oxygen species that create oxidative stress, which generates harm to cellular elements, including lipids, proteins and deoxyribonucleic acid. The oxidation damage leads to impairment of plant growth as well as decreased productivity [116, 184].

Soil salinity serves as a major environmental challenge for agriculture, which threatens food stability across African regions, particularly in dry areas. This develops as a combination of natural processes together with some human practices such as improper irrigation and inadequate drainage management [75]. The problem of soil salinity affects 80 million hectares primarily within arid and semi-arid areas of Africa while impacting about 180 million people at an estimated annual loss of $68 billion [117]. The insufficient monitoring and documentation of soil salinity in African croplands creates difficulties that worsen the situation [158].

Scientists have established different soil salinity management solutions through the use of organic and inorganic amendments and water-absorbing polymers together with integrated multiple-technique approaches. The use of gypsum was one of the common inorganic management technique. Soil reclamation through gypsum ($CaSO_4{\cdot}2H_2O$) application works by substituting Na^+ from clay particles with Ca^{2+} thus promoting better soil structure at the same time decreasing sodicity [27, 160, 172]. The process delivers numerous advantages to soil physical properties and enhances the ratio of Ca^{2+} to Na^+, and provides sulfur needed for amino acid production and protein synthesis [27, 160]. The application of this amendment achieve the reduction of soil pH and EC and sodium adsorption ratio (SAR) while improving soil quality and boosting agricultural production [25, 27, 172].

The application of water-absorbing polymers known as hydrogels represents a promising solution because they can absorb substantial water volumes while continuing to deliver it to plants [150]. The application of water-absorbing polymers enhances soil water retention, which in turn decreases irrigation requirements and enables proper plant development in saline areas [150]. Salt-tolerant plant growth-promoting rhizobacteria increase plant tolerance to salt through their ability to enhance both nutrient absorption and stress tolerance [60, 248]. Irrigation system that incorporates leaching methods with high-quality water supply assist in reducing soil salinity while maintaining soil structure [9, 150, 215].

A variety of organic materials, including compost, manure, biochar, vermicompost, and crop residues, have shown potential as strategies for improving saline soils [58, 88, 103, 127, 167]. Organic amendments improve plant stress tolerance, growth, and yield by enhancing ionic balance, photosynthesis, boosting antioxidant systems, and reducing oxidative damage [104]. Organic materials, when added to soil, create better structures and enhance organic matter (OM) levels [58, 88, 103, 127] and at the same time microorganisms function more effectively in nutrient cycling. These materials decrease soil salinity levels by improving water retention capacity and increasing soil fertility which results in better plant growth [58, 88, 102, 127, 167].

Soil salinity is a significant environmental issue in Africa, affecting about 80 million hectares (Mha), with 69 Mha located in Sub-Saharan Africa [117]. Challenges in using biochar for soil salinity amelioration in Africa include the lack of systematic research on their potential mechanisms [71, 73, 81]. The application of biochar generated from agricultural waste shows strong potential to enhance both soil quality and remediate soil salinity across African region and promotes agricultural sustainability alongside higher productivity which resolves some of the major obstacles encountered by African farmers. Biochar is charcoal made from the pyrolysis of organic materials [142]. The technique regarding biochar field applications as agronomic practice is relatively a new technique that is receiving increased attention as a viable way of improving soil quality [193]. Research demonstrated how biochar application improves the physical state of salt-affected soils. The improved physical properties of biochar-treated salt-affected soils represent a promising management method [15]. The adoption of biochar application to soils results in beneficial changes to salt-affected soil characteristics while specific biochar types and application rates may induce negative plant growth responses as presented in this article. Researchers have extensively studied the salinity remediation effects of biochar CEC yet there is limited presentation about biochar AEC's mechanisms and effectiveness for soil salinity mitigation which this article takes into consideration. This review evaluates biochar exchange capacities (CEC and AEC) as potential biochar characteristics that decrease soil salinity leading to improved crop yields. It also presents research works that uses soil EC as a salinity indicator to evaluate the impact of biochar on plant development in saline environments. Multiple investigations report positive outcomes, yet researchers have not studied methodically the functional roles of CEC and AEC in salinity amelioration processes. The purpose of this work is to draw attention to these gaps in knowledge while discussing the potential of biochar to lower ions that cause soil salinity. This review article also gave much insight into how biochar ameliorates soil salinity, focusing on both CEC and AEC while pointing out recent development and further research directions. Meanwhile, the study's main limitation is the lack of or few field research results confirming the efficiency of biochar to ameliorate soil salinity in different environments.

2 Extend of soil salinity around the world

Another global threat to agricultural yields reported by Ivushkin et al. [106] is an increase in the soil salinity. It affects more than one billion hectares of land spanning over one hundred countries across the world, and these numbers are ever on the rise [106]. Globally, saline soils cost agriculture at about $27 billion every year [201]. Reduction in crop yield, germination of seeds, water and soil quality and environmental degradation including instances of erosion and desertification, are all recognized to be worsened by salinity of the soil in areas of semi-arid and arid regions [176, 201].

In Europe, one of the most common causes of soil degradation is salinity, found throughout the Iberian Peninsula, Greece, Hungary, Romania, and Italy (Sustainable Agriculture and Soil Conservation, Soil Degradation Processes n.d.). In Europe, the estimated area affected by soil salinity was estimated to be around 1 to 4 Mha [74] (Table 1). It is considered a significant contributor to desertification and as such, a severe type of soil degradation. According to Sustainable Agriculture and Soil Conservation, Soil Degradation Processes (n.d.), salinization is becoming a more pressing issue in Europe due to recent temperature increases and decreases in precipitation. In Africa, approximately 80 Mha of land was reported to have been damaged by salinity [117]. Zamann et al.

Table 1 Area of land affected by salinity across some continents

Continent	Area affected by salinity (Mha)	Primary causes	Impacts on agriculture	Mitigation strategies	References
Europe	6.7	Unsustainable irrigation practices	Reduced crop productivity	Improved irrigation management	[74, 102, 145]
Africa	80	High evaporation rates	Soil fertility loss	Use of salt-tolerant crops	[117, 145, 168]
Asia	194.7	Sea level rise	Decreased water and mineral uptake in plants	Application of endophytic microorganisms	[55, 102, 249]
North America	69.5	Poor drainage systems	Groundwater contamination	Artificial drainage systems	[145, 188]
South America	6.2	Deforestation	Abandonment of agricultural lands	Governmental and private interventions	[52, 188]
Middle East	74.1	High temperatures and low precipitation	Water stress in plants	Use of essential nutrients like $K^+$and SO_4^{2-}	[197, 249]

[249] reported that 74.1 Mha of area in the Middle East experienced different degrees of impact due to soil salinity. Sahab et al. [188] reported salt-affected soils in South America and North America covering approximately 129.3 and 15.8 Mha with salinity affecting 69.5 and 6.2 Mha, while sodicity affecting 59.8 and 9.6 Mha, respectively. Zaman et al. [249] revealed that 194.7 Mha were impacted by salinity and 121.9 Mha by sodicity in Asia, highlighting the extensive scale of soil degradation in the region.

Soil salinity affects different regions throughout the world to various extents primarily because of a combination of natural forces and human-caused elements. In addition to this global assessment of the impacted region, there are several other estimations available, some of which significantly vary in their evaluation of the affected area [64] due to environmental [155], human [16] topographic and water table depths [24] as determining factors. Consequently, only a general approximation of the globally impacted saline area can be provided [106]. For example, soil salinity in the Middle East and parts of Asia becomes strongly affected due to the dry climate conditions [63, 72, 198]. Soil intrinsic features and geologic conditions directly affect salinity risks because naturally saline soils and areas that were located near saline water bodies have an increased likelihood of high salinity [63, 171]. Unsustainable irrigation practices together with high evaporation rates, sea level rise, poor drainage systems, deforestation, high temperatures and low precipitation represent major factors leading to desertification (More on Table 1; mitigation strategy, impact on agriculture). Soil salinity is not just a localized problem; it represents a formidable global problem that threatens agricultural productivity. Studies suggest that a significant portion of arid and semi-arid areas, comprising around 15% of the total, as well as approximately 40% of irrigated land globally, encounter substantial risks related to this abiotic element [159]. The presence of high levels of salts in the soil is a significant contributor to the decline in agricultural output and presents a significant obstacle to provide sustenance for the expanding global population [122].

Human activities, including inadequate irrigation drainage systems, have created extensive soil salinity problems particularly in intensively cultivated Asian and North American regions [72, 156, 166]. Urban development together with industrial growth intensifies salt accumulation by releasing wastewater and spreading de-icing road salts which both disproportionately affect dense urban and industrial areas [63, 166].

Extensive research shows climate change has intensified worldwide soil salinity problems mainly because of temperature rise and altered precipitation which enhances evaporation alongside hydrologic system disruption [23, 28, 47]. The largest area affected by salt salinity exists in Asia because of intensive agricultural practices and high human density under variable climatic conditions [72, 156]. The Middle Eastern region contains 74.1 Mha of affected land which stems from its dry arid climate together with irrigation systems [63, 198]. Saline soil covers significant areas of North American territory mainly because of agricultural operations combined with urban expansion and industrial activities in its dry regions [63, 156]. Africa experiences soil salinity damage from both natural dryness patterns and human-caused land management changes [63, 166].

3 Soil salinity measurement

An understanding of the temporal and geographical distribution of salt-affected soils and their recurrence possibility is essential for developing effective methods for land degradation restoration and mitigation, particularly in light of projected climate change scenarios [84]. Indicators of soil salinity include the following: white salt crust or salt stains on the soil surface, a swollen soil texture, erratic or nonexistent seed germination, leaf burning, reduced plant health, the presence of natural halophytes and worsening waterlogging following precipitation [196]. The dynamic nature of this soil salinity, which is characterized by notable geographical and temporal fluctuation, makes it difficult to map and continuously monitor across large regions [50].

Aqueous extracts from completely saturated soil pastes (ECs) or disturbed soil samples (ECe) are commonly used in lab settings to measure soil salinity [255]. Since EC rises by around 1.9% for every degree Celsius in the 15–35 °C range, the usual laboratory approach is questionable since it overlooks this effect [183]. Therefore, EC is measured and reported at a standard temperature of 25 °C to make comparisons easier [49].

Significant progress has been achieved in the last decade in creating quick and affordable methods for mapping and tracking soil salinity [206]. These methods (Table 2), which comprise both distant and close-range sensing technologies, provide a variety of instruments for determining the salt levels of soil [70, 144, 255].

4 Limitations in addressing soil salinity

Particularly in view of climate change, the prospects for soil salinity are concerning as global temperatures are expected to rise and therefore lead to repeated evaporation and consequently the formation of salt in the soil [85]. This is particularly worrying in areas where there are already high levels of salinity such as South Asia, Middle East, and sub-Saharan Africa.

Thus, there is still considerable impediment to combating global soil salinity. One of the main challenges is the high cost of desalination and soil reclamation technologies [258]. Despite their great efficacy in removing salt from soil or irrigation water, many farmers, especially those in developing countries, find these methods to be expensive. Most of the time, large-scale reclamation projects may require a great deal of capital investment and technical capacity, which the minor agricultural budgets of some countries cannot afford.

Another major problem is smallholder farmers lack knowledge and access to appropriate technology. Farmers lack the skills and expertise needed [87] to appropriately

Table 2 Various soil salinity measurement methods utilizing distant and close-range sensing technologies

Method	Type	Description	Advantages	Disadvantages	References
Visible and near-infrared reflectance spectroscopy	Close-range	Uses spectral reflectance data to estimate soil salinity	Fast, inexpensive, and can be used in the field	Requires calibration with ground truth data	[13, 152, 229]
Portable X-ray fluorescence spectrometry	Close-range	Measures elemental composition, which correlates with soil salinity	Quick and easy to use in the field	Requires laboratory calibration and may be less accurate for low salinity levels	[13]
Remote sensing (RS) with landsat and sentinel-2	Distant	Utilizes satellite imagery to map soil salinity over large areas	Covers large areas, frequent data availability	Lower resolution compared to close-range methods, requires calibration	[13, 38, 65, 216, 219]
Electromagnetic induction (EMI)	Close-range	Measures apparent electrical conductivity (ECa) as a proxy for soil salinity	Rapid, non-invasive, and can cover large areas quickly	Requires calibration with soil samples, affected by soil moisture	[92]
Multifrequency conductometry	Close-range	Uses varying frequencies to measure soil EC	Real-time, selective salinity measurement	Requires specific equipment and calibration	[89]
Unmanned aerial vehicle (UAV) based hyperspectral imaging	Distant	Uses UAVs equipped with hyperspectral cameras to map soil salinity	High resolution, flexible deployment	Expensive equipment, requires calibration	[92]

regulate the salinity of their soil in many regions of the world. Soil salinity is magnified by crude methods and inadequate irrigation and drainage methods. Also, prevention of salinization either at the regional or national level is a challenge because effort is fragmented by governance structures and a lack of efficient policy measures.

Global efforts to lessen the effects of climate change are linked to lowering soil salinity. Rising sea levels place coastal areas that are already suffering salinity intrusion in more danger, while upland areas are becoming more vulnerable to salinity as a result of changed rainfall patterns. To solve these issues, global climate change has to be managed internationally. However, this process has been slow, especially in the countries that are most directly affected by climate change. If these challenges are not redressed through adequate progress in water management and climate adaptation, global soil salinity remains a problem that threatens global agriculture and food security.

Reducing soil salinity can contribute to mitigating the impacts of climate change globally. It is becoming evident that increased sea level is threatening areas that were affected earlier by saline intrusion and simultaneously upland areas experiencing a change in rainfall, resulting in increased salinization. To address such concerns, climate change measures have to be coordinated internationally, and prior to the Paris Agreement, this effort has been slow: especially in areas that are most affected by the impacts of climate change [245]. It is forecasted that the global problem of soil salinization will aggravate, thus threatening agricultural productivity and food safety worldwide, unless a sustainable advance in water and climate stress management is achieved.

5 Impact of recent desert floods on soil salinity, challenges and limitations

Heavy rainfall experienced recently in the desert, which has become frequent and intense, was mainly because of climate change [61, 154], The Sahara Desert flooded for the first time in decades n.d.) These extreme weather events involve flash floods and offer significant amounts of water to areas that are originally scarce in water. At the same time, the role of such floods in controlling soil salinity is not entirely benign; presenting short-term advantages and long-term liabilities [12]. One of the impacts of floods is that they help in a way to alter the salt concentrations within the topsoil by physically removing salts for a short period [41]. This is especially the case in desert environments, where regularly low precipitation and high evapotranspiration mean that high salt concentrations are near the surface [197]. Given their geographic location and soil permeability, soils of these areas may remove soluble salts from the upper soil matrix and relocate them into deeper profile or out of the upper profile/layer when flood water sweeps the area [223]. This can enhance soil conditions for agricultural use as the immediate salt concentration around crop root zones threat plant health and growth [68]. For example, in the lands of the Middle East and North Africa where recent flash floods occurred, this first flushing effect lead to an increase in agricultural productivity right after the occurrence of the flood [187]. Farmers who struggle with saline soils may find much-needed relief from the reduction in surface soil salinity in agricultural systems that depend on seasonal rains or floodwater for irrigation, such as those found in dry riverbeds that momentarily fill with water during floods.

Furthermore, flash floods are typically characterized by raging torrents in response to heavy rainfall [86]. The water does not stay on the soil long enough to completely remove salts from deeper layers or to considerably replenish groundwater supplies [26, 223]. Rather, the concentration of salts in the topsoil can rise because of the water evaporating quickly in the hot, dry desert climate, creating conditions that are more salinized than they were before to the flood as seen in experiments with salt-crusted soils [130]. This phenomenon can be especially noticeable in areas with poor natural drainage or high clay soils that make it difficult for water to infiltrate through. The relief is only a short-term one because when the floodwater has drained away and much of it has subsequently evaporated, the result is an increase in salt concentrations. This is especially when the soil has poor infiltration and hence it is waterlogged, where very little water can penetrate the dry soil profile. Over time, the water dries up and the salts are moved back to the soil surface in these areas presumably making salinity worse and negatively affecting agriculture [10] (See Supplementary Doc. 1 for additional details and Table).

5.1 Transient leaching and re-accumulation by flooding and evaporation

Soil salinity changes substantially through transient leaching when flooding occurs. Soil and waste materials experience variable dissolved substance concentrations during transient leaching events because environmental patterns alongside hydrological flows modify substance levels in the soil [45, 141]. The processes of transient leaching differ from steady-state leaching because intermittent rainfall [165], irrigation [164], and chemical changes [37, 109] produce variable conditions leading to time-dependent fluctuations in solute transport dynamics and concentrations. The leaching process depends on hydraulic flow rate, together with dissolution–precipitation kinetics and sorption–desorption reactions and the medium buffering capacity [30, 186]. Multiple mathematical and numerical methods simulate solute leaching patterns through tracking transient concentrations and incorporate concepts from solute transport processes together with reaction speed measurements and equilibrium conditions [56, 114, 207] (See Supplementary Doc. 2 for additional details).

6 Mechanisms of biochar in alleviating salinity stress

Biochar functions as an effective salinity stress mitigation technology through processes that regulate ion exchange alongside quality enhancement of soil. One major way through which biochar functions to manage salinity occurs through regulation of ion exchange. The large surface area combined with porous structure of biochar allows it to actively adsorb and store Na^+ from the soil solution which reduces their availability to plant roots [71, 73, 94, 227]. Biochar raises soil CEC through which greater concentrations of K^+, Ca^{2+}, and Mg^{2+} as essential nutrients become available [71, 73, 94, 162] (Fig. 1). The better ion exchange capability of biochar leads to decreased SAR because it uses essential cations to replace Na^+ thus protecting soil from salinity-related damages [253]. Biochar plays two roles in improving soil quality by controlling ions along with enhancing the overall soil quality. Soil structure enhancement through biochar application creates stable aggregates that improve water retention and thus sustaining soil moisture levels while preventing root systems from osmotic stress [94, 133, 135, 227]. The use of biochar leads to higher soil carbon content while simultaneously maintaining essential nutrient elements N, P, and K availability in the soil [71, 73, 94, 133, 135, 162]. Microorganisms function more effectively within biochar-amended soils which aids the release of beneficial plant-growth-promoting substances while improving plant resistance to salinity stress [94, 227, 253].

Major interest exists in biochar mainly because researchers have recognized its ability to reduce soil salinity and boost farming output. Many research findings show how biochar influences salinity management in various complex ways. Biochar works primarily through adjustments that improve both the physical and chemical compositions of soil.

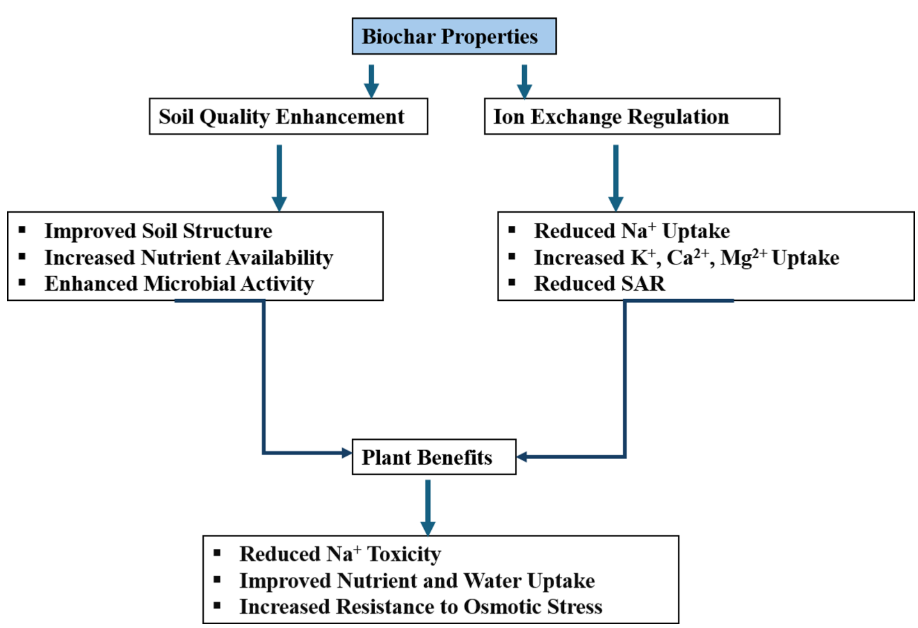


Fig. 1 Mechanism of biochar for soil salinity amelioration

Biochar improves soil structure and leads to enhanced porosity as well as greater aggregation and improved water retention capacity thus supporting soil moisture needs which combat osmotic stress in saline environments [18, 210, 218, 227] (Table 3). The retention of nutrients through increased CEC benefits plants because it prevents unnecessary nutrient leaching and ensures better nutrient access [18, 162, 218]. Biochar functions as a buffer to maintain stable soil pH levels which occur in connection to saline conditions [18, 227].

The main role of biochar in salinity stress mitigation occurs when it adsorbs and exchanges ions from the soil solution. Biochar functions as an effective adsorbent for Na^+ which binds them in place while reducing their availability to plants [18, 227]. Biochar achieves two beneficial effects by lowering salinity effect and enabling better nutrient uptake under saline conditions [18, 71, 73, 227]. Biochar supports beneficial microbial communities in the soil by means of its positive effects. The presence of biochar enables soil microorganisms to function properly, thus aiding in OM decomposition and nutrient cycles that sustain soil quality under saline conditions [18, 71, 73, 210]. Biochar promotes soil enzymatic activities due to which plants tolerate oxidative stress better through enhanced antioxidant enzyme performance [71, 73, 107, 162].

The improved soil characteristics as well as biological functions, create positive effects on plant development and growth. Biochar use under saline conditions has been shown through empirical studies to enhance three fundamental growth indicators namely plant height and biomass for roots and shoots as well as crop yield [97, 103, 180]. The application of biochar enables plants to maintain proper ion balance while simultaneously improving photosynthetic operations and defending against oxidative stresses and enhancing antioxidant capacities [48, 71, 73, 97].

Biochar performance in salinity control functions differently based on the conditions under which it is applied. The proper biochar application requires adjustment from 20 to 50 tons per hectare (t/ha) based on soil type together with salinity level [180, 231]. The performance levels of biochar depend on two essential factors, which include the type of feedstock material and the temperature of pyrolysis. Research shows that increasing the temperature during biochar pyrolysis between 450 and 550 °C leads to improved soil functionality combined with stronger salinity stress reduction effectiveness [18, 231]. The successful implementation of biochar as a salinity management technique depends on proper evaluation of its source materials and application levels while considering specific soil conditions.

Table 3 Summary of the biochar mechanism for salinity management

Benefit	Mechanism	References
Improved soil structure	Enhanced porosity, aggregation, water retention	[18, 210, 218, 227]
Nutrient retention	Increased CEC, reduced nutrient leaching	[18, 162, 218]
pH buffering	Stabilizes soil pH	[18, 227]
Ion adsorption	Adsorbs harmful ions (e.g. Na^+)	[18, 227]
Enhanced microbial activity	Boosts nutrient cycling and OM decomposition	[18, 71, 73, 210]
Increased enzymatic activities	Mitigates oxidative stress in plants	[71, 73, 107, 162]
Improved plant growth	Enhances biomass, yield, and physiological traits	[102, 180, 180]

7 Biochar, soil salinity and electrical conductivity

The EC of a soil solution means its ability to transfer electricity because pure water has a low EC [35]. The EC of the solution rises in proportion to the concentration of soluble salts 54. As a result, higher EC values of soil indicate that the soil contains salt. Leaching appears to be a practical way to reduce the excessive amount of soluble salt in saline soil (Das et al., 2022).preve According to findings, biochar helps soluble salts drain, which lowers the EC and salinity of the soil profile [208, 246]. Saifullah et al. [189] and Tuyishimire et al. [226] also suggested that biochar enhances soil porosity and hydraulic conductivity and therefore accelerates the rate of soluble salt leaching in the soil, which consequently reduces ECe.

Thus, to learn more about the effects of biochar on the mobility of salt and its ability to further condition the soil, Yue et al. [247] carried out an experiment. According to their research, biochar-modified soil columns showed a salt efflux 24–40 days earlier than unmodified soil. The time needed for the efflux's EC values to drop to 5 dS/m was shortened by the addition of biochar, which accelerated salt leaching. Additionally, the salt washout period in the soil column was reduced to 56 days from 62 days by the addition of biochar [247]. This was possible as biochar lowers down the EC of saltine soil by enhancing the hydraulic conductivity and porosity of the soil.

7.1 Influence of biochar on saline soil EC

According to Qadir et al. [173] and Qadir et al. [174], to avoid high salt accumulation in the root zone, adequate irrigation that exceeds evapotranspiration and drainage is required. They further stated that, with adequate groundwater depth, soil drainage can be improved by incorporating amendments that improve salt leaching and soil porosity, promoting favourable conditions for plant root growth. Chaganti et al. [40] observed significant reductions in ECe of a saline-sodic soil with clay loam texture and low OM content when amended with biochar (alkaline pH), biosolids compost, and green waste compost. Their results showed significant reductions in ECe respectively in contrast to untreated soil. These reductions were attributed to enhanced soil hydraulic conductivity, facilitating the leaching of salts in the soil matrix. In a separate 2-year field study, Lashari et al. [123], reported a high decrease in ECe of saline-sodic soil through the simultaneous use of biochar and poultry manure compost in contrast to untreated soil.

However, Hammer et al. [82], proposed different mechanisms for the reduction in ECe and salinity stress due to biochar application. They linked the decrease in ECe to salt formers such as Na^+ being adsorbed on biochar surfaces and trapped in fine pores. According to their findings, this reduced soil solution salt concentration, while decreasing evaporation under biochar application reduced upward movement of saline water, leading to reduced salt accumulation on surface soils. It is essential to consider that the effectiveness of biochar in reducing salinity relies on factors such as biochar type, aging time, and the strength of salt attraction on biochar. Salts adsorbed by biochar or trapped in fine pores might be released back into the soil solution over time [11]. Additionally, when low-salinity water is used for leaching, calcium and magnesium salts are preferentially leached away, while sodium is more slowly leached and eventually dominates the soil (Gupta et al. 2021). This results in an increase in SAR and exchangeable sodium percentage (ESP), transforming the soil into a saline-sodic or sodic condition.

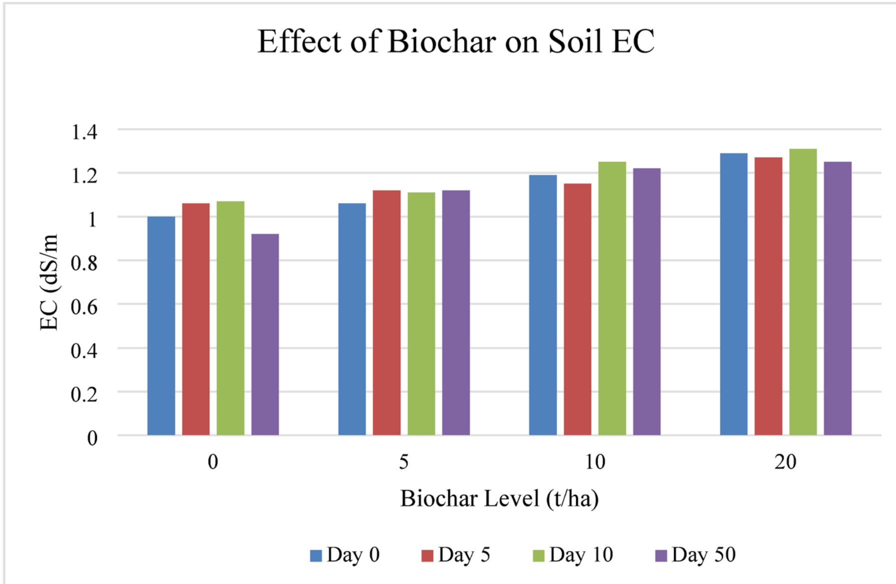


Fig. 2 Effect of biochar application on soil EC without leaching

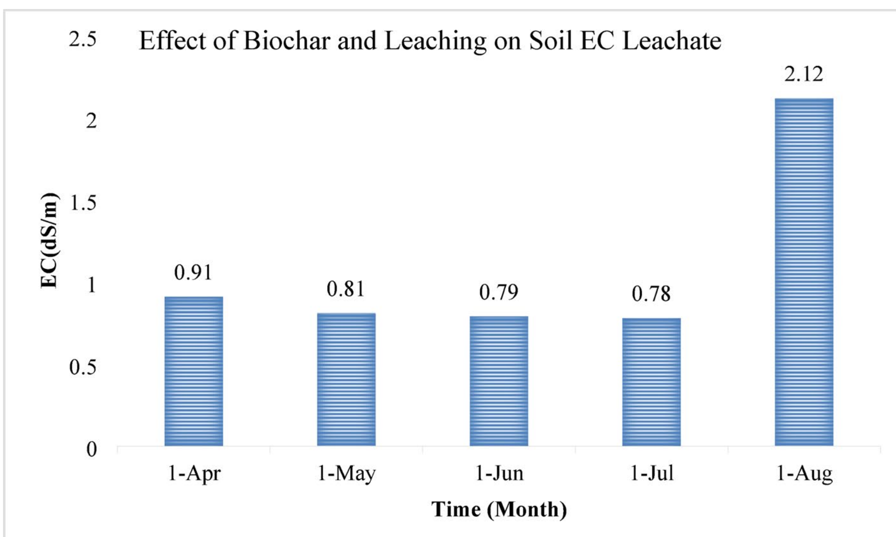


Fig. 3 Effect of biochar and leaching on soil leachate EC

Moreover, biochar derived from Acacia tree branches and trunks affected the EC measurements in silty clay loam soil during a 50-day incubation study (Fig. 2) according to Shah and Shah [195]. Soil samples with biochar showed elevated EC measurements above those of the unamended control according to the experimental data used (Fig. 2). This may occur due to insufficient leaching of salt from the soil which leads to increased EC according to Moradi et al. [147]. In contrast, Sorrenti and Toselli [204] conducted a leaching experiment on hardwood-derived biochar (20 g/kg) in sandy soil to find out changes in EC which demonstrated dissimilar results from Moradi et al. [147] findings. Their study revealed that leachate EC measurements rise in the 5th month (Fig. 3), indicating that biochar might potentially diminish soil EC levels. The better soil hydraulic conductivity from biochar application may have led to better salt leaching from the soil [67].

8 Biochar and its possibility for soil salinity remediation in soil: focus on CEC and AEC

Biochar plays a major role in reducing salinity stress in soils by affecting their ion exchange behavior through CEC along with minor impacts from AEC. The numerous negative functional groups along with increased surface area of biochar result in elevated CEC capacities that enable retention of Na^+ cations and inhibit their movement toward damaging soil and plant systems [22, 71, 73, 162]. The replacement of Na^+ ions with preferred cations Ca^{2+} and Mg^{2+} is supported by biochar, simultaneously benefiting soil structure and fertility [71, 73, 128]. Biochar properties during pyrolysis influence the extent of CEC enhancement through heat application because temperatures above 550 °C produce better exchange properties and reduced toxic residues [221]. Biochar generally affects CEC but shows limited influence on AEC with respect to Cl^-. Biochar indirectly helps control chloride ions (Cl^-) by improving soil structure and water retention which enhances anionic leaching and distribution [83, 218]. Cl^- ion adsorption on biochar surfaces occurs mainly through physical adsorption and weak ion exchange but does not reach the effectiveness of cation dynamics [218].

The exceptional characteristics of biochar that aid in mitigating g soil salinity include improved soil porosity together with increased water holding capacity and hydraulic conductivity which establish beneficial growing conditions for plants under saline environments [128, 180, 218]. Biochar increases CEC which functions as a nutrient retention system that minimizes nutrient waste as well as enhances plant availability of nutrients [71, 73, 162]. In addition, it also supports bacterial activities within soil which are essential for nutrient circulation and soil health to enable stronger resistance against salinity stress [83, 211]. The carbon-rich biochar derived from agricultural waste through pyrolysis shows excellent potential for lowering soil salinity by modifying both CEC and AEC which affects Na^+ and Cl^- ions.

According to Gunarathne et al. [77], wood chip biochar, produced at 500 °C has been found effective in decreasing soil salinity through leaching, particularly in cases of intensive irrigation. Huang et al. [95] reported that the incorporation of woodchip biochar into soil led to a significant reduction in soil EC compared to untreated soil. The reduction ranged from low to high in the incorporation zone and low to moderate in the lower incorporation zone. Saifullah et al. [189] identified two primary reasons for this EC reduction: firstly, the physical adsorption of salts in the microscopic pores of biochar, or the adsorption of Na^+ on its surfaces. Secondly, the decreased deposition of salts on the soil surface due to biochar-induced reductions in upward movement of saline water, attributed to the covering effect of biochar that mitigates evaporation.

Rostamian et al. [185] found that rice husk biochar with alkaline pH, low EC, with an average pore size of 2.2 nm, effectively captures Na^+ ions with a radius of around 0.178 nm. Ion exchange is another mechanism for salt removal. Gurmu [79] reported that OM contains negatively charged sites generated by the dissociation of organic acids in the soil, which attract and retain cations, thereby contributing to the soil CEC. The presence of negatively charged sites on OM can have a significant impact. Research by Fageria and Gheyi (2009) demonstrated that, increasing the level of OM in the soil also increases its CEC. Previous studies have established a correlation between the CEC of biochar and its salt ion adsorption capacity. The CEC varies with feedstock and production conditions, closely tied to the concentration of oxygenated functional groups present on the biochar surface. Yavari et al. [241] indicated that the presence of oxygenated and polar functional groups, including hydroxyl, carboxyl, and carbonyl groups, contributes to a high CEC value of 83.90 cmol kg^{-1} for biochar. These functional groups are believed to play a role in salt adsorption. The oxygen-carbon (O/C) ratio appears to influence the hydrophilicity of the biochar surface. Higher polarity of surface functional groups and improved adsorption capacity are correlated with increasing the O/C ratio. Two mechanisms by which the addition of biochar improves CEC in soil were found by Chan et al. [42]: first, the large surface area of biochar enhances the adsorption process. Secondly, the high charge density of biochar favoured in retention of positive ions like Na^+. Tan et al. [218] additionally commented about the possible ways that biochar improves the quality of saline soil, with a particular emphasis on ionic exchange and physical adsorption. These processes result from the unique characteristics of biochar, including its high porosity, large surface area, abundance of functional groups and high carbon content [53] (Fig. 4).

An et al. [18] reported in their research that the application of biochar helps in reducing the bulk density of the soil provided that the particle sizes are larger. Cao and She [39] also confirmed the positive effect of biochar on the improvement of the soil hydraulic properties in a disk infiltration experiment. According to their results, 2% biochar application boosted the hydraulic conductivity of the coastal saline soil significantly

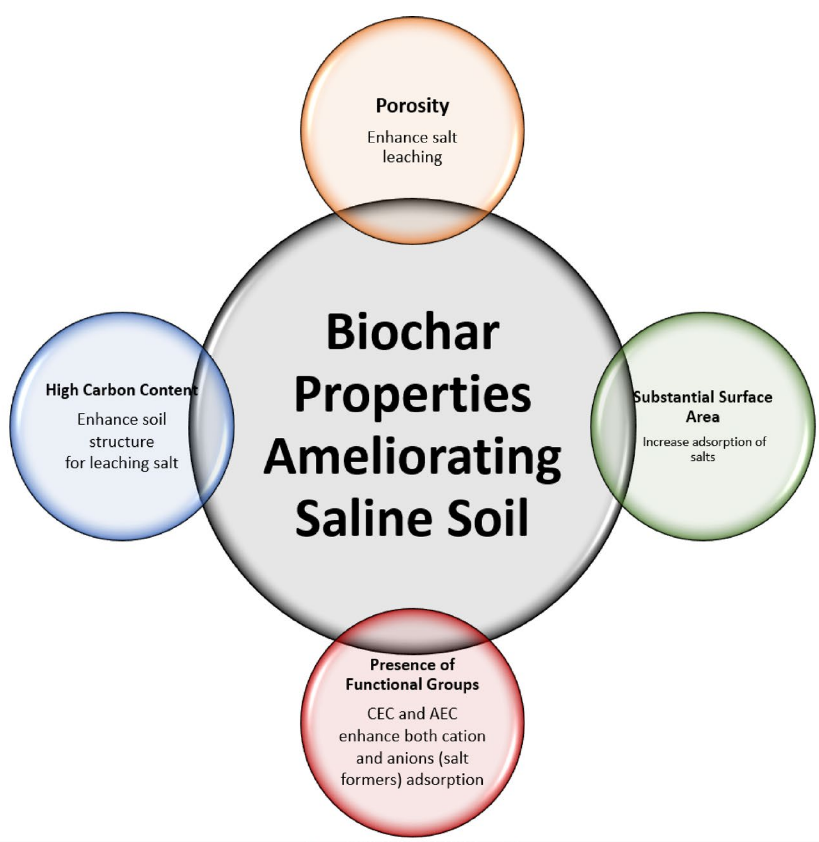


Fig. 4 The features of biochar that improve soil salinity

by 46.4%, in comparison to the control. As claimed by Hossain et al. [90], the practical application of biochar improves the value of soil porosity by 2 to 4% percent which has a direct effect whereby, it reduces the bulk density of the soil.

The addition of biochar raised soil porosity by 8.4%, and the increase was linearly proportional to the amount of biochar used [157]. Low-density biochar particles increase soil porosity, bulk density, and particle density [33]. Biochar improves soil structure when added to sandy soil [237]. This structural improvement is the result of increased hydraulic conductivity and porosity, which allows more water to infiltrate [4]. If the water penetrates through the soil, leaches out salts, which are in the soil and therefore reducing salinity.

Biochar functions in improving the quality of saline soil by lowering its salt concentration as demonstrated by the enhanced hydraulic conductivity, which further improves the leaching process. Surface functional groups such as carboxylic (–COOH), hydroxyl (–OH), amine, amide, and lactonic groups improve the sorption capabilities of biochar; however, an increase in surface area, porosity, and pH may decrease these functional groups [108]. These functional groups increase the soil CEC, which enriches it in cation adsorption, such as Na^+. Addition of organic substances facilitates Na^+ removal from the exchange complex through release of Ca^{2+} and Mg^{2+} [108]. Biochar also releases cations such as Ca^{2+} and Mg^{2+} with additional advantages of being recalcitrant, high CEC and AEC contribution over the later applications. Soils that have higher CEC tend to selectively draw polyvalent cations rather than monovalent ones from the soil solution, which is a colloid-specific phenomenon [228]. This aids the leaching of Na^+ easily in the soil rhizosphere.

In saline soils, organic amendments assist in enhancing the removal of salts from the soil by: (1) enhancing and preserving soil porosity, thereby improving water movement within the soil [224], and (2) boosting root function and growth, leading to enhanced soil structure and the formation of water channels, thereby promoting increased water movement in soil [234]. Organic amendments have the potential to enhance the breakdown of naturally occurring calcite ($CaCO_3$) minerals by promoting the increased formation of carbonic acid in the soil profile [174]. To further displace Na^+ from the cation exchange sites, this dissolution may release Ca^{2+} into the soil solution [239]. It is known that biochar raises the CEC of soils. A phenomenon unique to colloids, this high CEC selectively extracts polyvalent cations from the soil solution instead of monovalent ones [228]. By increasing the soil CEC, organic amendments reduce the exchangeable sodium percentage (ESP), increase the soil preference for Ca^{2+} over Na^+, and prevent sodic behavior by increasing the hydrophobicity of organic compounds [181].

Physical adsorption is a well-defined reason for the higher mobility of cations when interacting with biochar compared to mechanisms such as attraction, ion exchange, adsorption and also formation of complexes. The surface charge produced by negatively charged surface groups, which is more negative at higher pH values, determines the intensity [46]. Research findings indicate that biochar's strong electronegativity might electrostatically attract positively charged ions [7]. Normally, biochar is proven to have good CEC and may release cations such as Ca^{2+} and Mg^{2+}. By exchanging it on the surfaces of the biochar, these cations may easily replace excess Na^+ in the soil. Furthermore, the functional groups found on the surfaces of biochar improve the CEC of the soil, which promotes complex formation and increases the soil's adsorption capacity. Cheng et al. [44] found that biochar made from oak using conventional kiln procedures had moderate AEC of 9.92 and 6.96 cmol kg^{-1}. Biochar has been found to exhibit anion exchange properties, although most studies primarily focus on CEC [193], Fig. 5. In research conducted by Inyang et al. [101], moderate AEC values of 6.64 and 11.19 cmol kg^{-1} were measured for biochar derived from sugarcane bagasse and anaerobically digested bagasse, respectively, through pyrolysis at 600 °C. Silber et al. [200] also reported a stable moderate AEC of 15.4 cmol kg^{-1} across the pH range of acidic to alkaline (4 to 8) for a maize stover biochar produced at moderate temperature of 500 °C.

Cheng et al. [44] conducted research on biochar, measuring AECs ranging from low to moderate (1.8 to 8.4 cmol kg^{-1}) for freshly prepared biochar and those incubated for 12 months at 30 °C. However, no AEC was detected for biochar recovered from historical kiln sites or for fresh biochar that had been incubated for 12 months at 70 °C. Mukherjee et al. [149] did not observe AEC in Oak (*Quercus lobata*), pine (*Pinus taeda*), and grass (*Tripsacum floridanum*) biochar produced at 400 and 650 °C under N_2 purge. Ahmad et al. (2013) suggested that AEC could be attributed to the protonation of carboxylate and/or ether groups at low pH, referencing studies on biochar-mediated heavy metal-oxyanion sorption. However, this mechanism appears implausible considering that the acid dissociation constants (pKas) of protonated and positively charged benzoic acids and phenyl ethers are in the − 6 range. A study by Lawrinenko et al. [125] reported varying AEC ranging from low to high (0.602 to 27.76 cmol kg^{-1}) for biochar derived from alfalfa, cellulose and maize stover. The authors identified oxonium groups, pyridinium groups, and the adsorption of protons by the basal planes of π ring systems in condensed aromatic carbon as potential sources of the positive charge responsible for AEC [124].

Significant AECs were found in biochar made from a variety of feedstocks [200]. Interestingly, they discovered that biochar that had been equilibrated at pH 4 had much higher AEC values than those that had been equilibrated at slightly acidic to alkaline pH of 6 or 8. Pyridinium groups, oxonium groups, and protonated aromatic rings were the three possible sources of AEC that the researchers investigated in the biochar under study. They suggested that the functional groups in charge of biochar AEC are heterocycles of nitrogen and oxygen. According to earlier studies, biochar contains pyridinic and

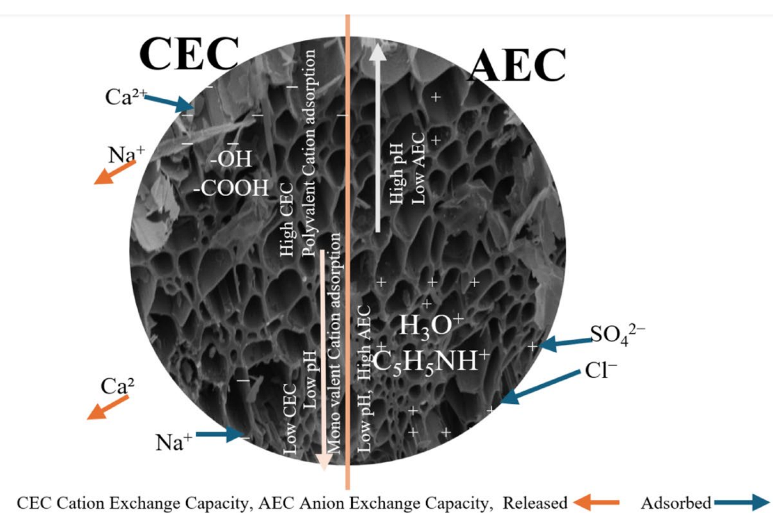


Fig. 5 How biochar influence soil salinity based on CEC and AEC

pyrrolic/pyridone forms of nitrogen [140]. While pyridone and pyrrolic groups are neutral, pyridinic groups carry a + 1 formal charge and become protonated at pH below their pKa, suggesting that they might be related to AEC. Similarly, it was proposed that nitrogen and oxygen heterocycles, particularly pyridinic groups with a + 1 charge at lower pH, are the cause of AEC in biochar [69, 181].

According to Lawrinenko and Laird [124], heterocyclic oxygen can have a pH-independent + 1 formal charge when sp2 hybridized, as is the case with pyrylium, an oxonium heterocycle, or it can be electrically neutral in the case of cyclic ethers and pyrones. Thus, another possible source of AEC in biochar are the oxonium groups. Despite the fact that biochar is known to contain substantial amounts of O and some N, little is known about the precise functional forms of these elements in biochar and how the conditions of pyrolysis affect the formation of particular functional groups in biochar.

Additionally, 13C nuclear magnetic resonance spectroscopic analysis has been used to identify O heterocycles in biochar generated from rice straw [129] and maize stover [101]. Also, the precise functional forms of these elements and how pyrolysis circumstances affect their production in biochar are yet unknown, despite the fact that biochar include a significant amount of O and some N. Oxonium groups are found in biochar and contribute to the observed AEC [69, 124, 129, 140]. The AEC of washed rice biochar was 26 cmol kg^{-1} in a more recent work by Dey et al. [57], but after being modified with ozone and HCl-$FeCl_3$, it rose to 58.1 cmol kg^{-1}.

Surface complex reactions are essential for managing soil salinity. Certain anions, such as Cl^- and sulfate (SO_4^{2-}), are components of salts. In moderate amounts, these ions are essential for plant growth. However, when present in excess, they contribute to soil salinity. High concentrations of these anions can disrupt the balance of soil chemistry and impede the growth of most plants. The presence of AEC in biochar could influence anions such as CI^-, SO_4^{2-} that form salts in soil. Biochar with AEC can adsorb harmful anions like CI^- and SO_4^{2-}. This restorative action is especially significant in soils with limited leaching capacity as they can be rendered unavailable to some level of insignificant effect by the adsorption process. By removing these harmful anions from the soil solution, biochar helps restore the natural balance of salts in the soil, creating conditions that are conducive to healthy plant growth.

9 Effective biochar types for soil salinity mitigation

A systematic evaluation of biochar salinity mitigation requires analysis of three essential aspects which include feedstock type and pyrolysis parameters as well as core physical and chemical characteristics. Under saline soil conditions, various feedstock materials produce different levels of effectiveness as biochar solutions. Poultry manure biochar demonstrates exceptional performance for improving soil microbial biomass and nutrient availability because of its favourable ash content and low carbon-to-nitrogen ratios (C:N) ratio that makes it suitable for saline environments [139]. The biochar derived from farmyard manure shows exceptional efficiency in improving agroforestry species growth alongside their physiological function under saline soil conditions [243]. Sugarcane bagasse biochar shows excellent ability to improve soil properties together with plant growth performance in calcareous soils, according to Rassaei [180]. Wood-based biochar provides solution against salinity stress and enhances plant developments [243] but rice straw biochar supports soil K composition and carbon accumulation, which assists saline soil conditions [139].

The key factors of temperature, heating rate and residence time during biochar production determine the final quality of biochar products as well as their functional properties. Biochar produced at temperatures exceeding 550 °C demonstrates diminished functional groups while maintaining structural integrity hence enhancing its efficiency to combat soil salinity and strengthen plant growth [218, 221]. Biochar produced within the temperature range of 350 to 550 °C demonstrates the best performance by acquiring larger surface area and porosity, which improves its ion absorption capability [51, 80]. Furthermore, the heating rate and residence time during pyrolysis also play critical roles. Scientific studies demonstrate that heating biochar at 10 °C/min yields optimal structural features and heat treatment for 30–60 min strengthens biochar stability alongside nutrient retention for better salinity management [51, 80].

Biochar performance for managing saline soils depends greatly on its essential physical and chemical characteristics. Most biochar naturally exists at high pH values extending from 9.3 to 10 which acts to buffer acidic conditions and create a beneficial environment within saline-stressed soils [100]. The specific surface area (SSA) of biochar becomes crucial because it boosts water retention together with nutrient holding capacity which enables better plant performance under salinity stress [143]. The high CEC property of biochar enables better soil fertility through essential cation retention and exchange thus improving soil nutrient availability while reducing salinity stress [6, 143].

10 Biochar source, particle size, and soil salinity remediation

From scientific findings, saline soil remediation effects from biochar materials depend on their specific chemical and physical characteristics based on different sources such as crop residues, wood and manure materials (Table 4). According to Amini et al. [17], effective reclamation of salt-affected soils with biochar requires careful consideration of soil properties such as texture, nutrient content, and native carbon as well as biochar characteristics, including its pH and feedstock source. They stated that in saline soils, biochar may increase or decrease EC depending on its nature, enhance soil organic carbon (SOC) stocks and improve plant growth and yield. While in saline–sodic soils, biochar can raise SOC, alter pH and SAR based on its properties and improve water-holding and hydraulic conductivity. Moreover, they reported that in sodic soils, biochar contributes to increased total and aggregate-associated SOC, enhances water-holding and hydraulic properties, and boosts microbial biomass carbon. Different biochar sources made from crop residues such as sugarcane and grape pruning showed effective results in enhancing soil conditions [19, 20]. The application of sugarcane biochar produces multiple beneficial effects on soil which promote plant growth by improving

Table 4 Biochar sources, size and their effect on soil salinity

Biochar source	Effect on soil salinity	Optimal particle size	Benefits	References
Crop residues	Reduces salinity, improves soil properties	Intermediate (0.5–2.0 mm)	Enhanced plant growth, nutrient availability	[147, 180]
Wood	Enhances soil quality, phytoremediation	Intermediate (0.5–2.0 mm)	Improved plant growth, soil remediation	Li et al. (2021), Pan et al. (2022)
Manure	Improves physical properties, water retention	Intermediate (0.5–2.0 mm)	Better soil structure, nutrient retention	Šimanský et al. (2022)

pH values and decreasing EC and raising soil OM levels [180]. Similarly, grape pruning biochar supplemented with rock phosphate and cow manure shows effectiveness in lowering soil pH while simultaneously releasing essential nutrients including phosphorus, iron and zinc which lead to better saline soil remediation [147]. Bamboo and sawdust feedstocks as wood sources present effective biochar for improving soil quality and helping plant development. Research demonstrates that bamboo biochar shows exceptional performance in phytoremediation solutions for multi-metal contaminated soils because of its applicability across wider soil remediation settings (Li et al. 2021). The application of acid-modified sawdust biochar proves effective for both reducing soil salinity and fostering plant growth (Pan et al. 2022). Studies have shown that biochar made from manure combined with farmyard manure enhances both soil pore distribution and water retention capabilities which support salinity mitigation efforts (Šimanský et al. 2022).

Particle size represents a fundamental variable which determines how effective biochar will be for salinity control. According to reports, the enhancement of water retention and nutrient exchange occurs better with small biochar particles (≤ 0.5 mm), but these fine-textured particles worsen salinity stress when salt levels are high [231], Liao and Thomas 2019). When it comes to liming effect, increasing soil pH and water-holding capacity, biochar of small particles performs more effectively (Liao and Thomas 2019). The most effective particle size range for plant growth promotion under saline conditions consists of intermediate sizes ranging between 0.5 and 2.0 mm [220] (Table 4. Biochar particles above 2 mm aid salt leaching and improve nutrient cycling to reduce soil salinity effects and potentially enhance crop production rates but their success depends on soil type along with which crop grown in a specific area [231].

Biochar application rates also vary significantly according to the type of biochar and the specific soil conditions. Rates from 2%, 50 t/ha have been reported to be effective (Table 5). Different biochar types from residues, manure and wood have shown varying degrees of effectiveness in mitigating soil salinity. For specific conditions like wastewater irrigation, sewage sludge biochar can be effective [31].

11 Positive role of biochar under different texture and regional conditions in ameliorating soil salinity

Biochar serves as a beneficial solution for improving soil salinity across multiple geographic areas of Europe, Africa, Asia, North America, South America and the Middle East yet local environmental conditions and soil types determine its specific effectiveness. Biochar applications in temperate agricultural soils across Belgium led to enhanced SOC content together with improved C:N ratios but studies revealed unstable outcomes for different soil types over successive time periods [153]. Biochar applications in Egyptian soil improved both fertility and reduced salt content in saline-sodic areas which boosted maize crop production [136]. Asia has demonstrated reliable performance benefits when using biochar. Biochar applications to coastal Chinese saline-alkali soils produced better soil conditions while enhancing soil fertility and increasing plant crop output [221, 250]. Moreover, biochar application in paddy fields both increased rice production while simultaneously improving the quality of saline soils [256]. Biochar applications demonstrate proven ability to improve soil quality along with agricultural yield production in North American sulfate-dominant salt-affected land [231]. Available research from South America shows that biochar demonstrates aptitude as a potential

Table 5 Biochar source, application rates and their effects on soil salinity

Biochar source/type	Application rate	Effect on soil salinity	References
Wood	6% w/w	Improved soil properties, reduced soil EC and SAR, enhanced plant growth	[32]
Wood	1.5% w/w	Increased biomass and plant height, improved soil properties	[242]
Wood	4–6% w/w	Reduced soil cracking, improved soil structure	[252]
Wood	57 t/ha	Reduced soil respiration, increased plant grain yield	[169]
Wood	20 t/ha	Improved rice biomass, chlorophyll content, and overall growth	[83]
Farmyard manure	6% w/w	Best for promoting growth and physiological parameters of tree species	[243]
Farmyard manure	3–9% w/w	Enhanced growth and physiological characteristics of agroforestry tree species	[32]
Sugarcane bagasse	6% w/w	Improved growth of *D. sissoo* compared to wood biochar	[243]
Rice husk	25% w/w	Improved soil quality, increased soil fertility, reduced soil salinity	[83]
Sunflower husk	2% w/w	Increased adsorption of heavy metals, improved soil properties	[36]
Grape pruning residues	2% w/w	Reduced soil pH, increased nutrient content, lowered sodium concentration	[147]
Cow manure	5–10 t/ha	Improved soil quality, increased rice biomass and growth	[83]

solution for strengthening soil characteristics during plant cultivation under saline soil conditions in that geographic area. Weathered soils of Middle Eastern areas receive significant enhancement after biochar treatment which effectively boosts soil productivity when used in regions with saline water irrigation systems [202]. The worldwide research indicates that biochar presents effective salinity management solutions across different climates and soil types. However, studies focused on specific local conditions would boost its acceptance in broad-based salinity management practices.

Scientists acknowledge biochar as a successful soil remedy against salinity, but its performance depends on various aspects of soil texture and application techniques. Biochar applied to coarse-textured soils creates remarkable improvements regarding field capacity (FC) and available water capacity (AWC) while showing greater effectiveness than medium- or fine-textured soils [230]. Biochar applications show positive effects on water retention and salinity reduction in medium-textured soils but produce weaker outcomes than what is observed in coarser soils [230] (Table 6). Biochar applications in fine-textured soils have minor effects on water retention but simultaneously improve soil structure and reduce salinity [111, 230]. The literature shows that biochar applications from 10 to 30 t/ha yield satisfactory results for improving soil conditions alongside salinity reduction [175, 220]. The effective operation of biochar depends notably on the properties it develops during production between 450 and 550 °C with a carbon–nitrogen ratio of 40–60 and high SSA [138, 231]. Biochar when combined with inorganic fertilizers or polyacrylamide produces enhanced synergistic effects improving both soil quality and crop productivity under saline conditions [3, 231]. Therefore, soil salinity mitigation could also reach its effectiveness through optimized biochar applications which consider both soil textures and biochar characteristics alongside integrated management approaches.

Table 6 Biochar effectiveness in soil salinity amelioration under different soil texture

Soil texture	Effectiveness	Optimal application rate (t/ha)	Notes	References
Coarse-textured	High improvement in water retention and salinity reduction	10–30	Significant increase in FC and AWC	[230]
Medium-textured	Moderate improvement in water retention and salinity reduction	10–30	Effective but less pronounced than in coarse-textured soils	[230]
Fine-textured	Lower improvement in water retention but effective in reducing salinity	10–30	Improves soil structure and reduces salinity	[111, 230]
General conditions	Effective in various soil types and climates, especially when combined with other amendments	10–30	Combining with fertilizers or PAM enhances effectiveness	[3, 231]

The effectiveness of biochar-amended soil in reducing salinity requires analysis of the temporal patterns and salt drainage characteristics within biochar-modified substrates. Both the original biochar characteristics and the amount applied to the soil determine when salts will be released into the surrounding area. According to Yue et al. [247], biochar application in soils leads to increased efficiency of salt leaching while decreasing both efflux discharge time and EC value decline duration. The dissolution rate of salt compounds from biochar-amended soils increases due to changes in soil physical and chemical properties through which biochar influences both the timing and extent of release (Xu et al. 2023). Biochar improves soil structure as well as long-term water retention functions while delivering short-term salt movement benefits to the soil [105]. Stabilized soil moisture levels through these improvements decrease the osmotic stress on plants and increase their ability to survive under saline environments [102, 227]. Through its dynamic corelation with various soil characteristics, the dynamic nature of biochar behaviour enhances its immediate salt reducing properties while building sustainable soil health systems under salt-stressed conditions.

12 Response of crops to biochar application under salinity conditions/stress

Rezaie et al. [182] highlighted that biochar exhibits the potential to confer salt tolerance to plants through various mechanisms. These include enhancing soil properties such as porosity, EC, water holding capacity, pH, hydraulic conductivity, soil structure, Na^+ adsorption, SOC content, nutrient availability, enzymatic activities, cation–anion exchange, microbial abundance, nitrogen-fixation capability, and colony-forming unit properties. A summary of biochar application results on some crops under salinity stress is presented in Table 7.

To illustrate these findings further, in a recent pot experiment on sandy soil with a bulk density of 1.38 g/cm^3, Zhang et al. [251] investigated the effects of wood biochar and poultry manure biochar with pH 8.6 and 10.1, both derived from chemically untreated wood. By improving soil texture, water retention, and slowing ion uptake, they argued that biochar application could mitigate the adverse impacts of deficit irrigation and salt stress (0, 0.1, and 0.2 mol/L NaCl). This approach alleviates osmotic and ion-related stresses on crops, promoting optimal internal water balance. Furthermore, the application of biochar facilitated increased transpiration rates and enhanced plant water absorption, providing a favourable environment for tomato seedling growth under conditions of salt and drought stress.

Table 7 Summary on response of crops to biochar application under salinity condition/stress

Feedstock	Temperature (°C)	Experiment	Salinity stress	Effect	Author(s)
Wood and poultry manure biochar	550	Pot	0, 0.1 and 0.2 mol/L NaCl	Enhanced plant water uptake and increased transpiration rates, providing beneficial conditions for the growth of tomato seedlings even when subjected to salt and drought stress	[182]
–	–	Pot	1500 and 3000 ppm	The application of biochar led to increased crop yields	[62]
–	–	Pot	1600 and 2800 ppm NaCl	Following transplantation and exposure to 2800 ppm NaCl stress, rice exhibited an extended lifespan of up to 80 days	[120]
Rice straw	400	Pot	0, 6 and 12 dS/m NaCl	The negative impacts of salinity were mitigated by enhancing plant growth traits, physiological functions, ionic behavior, and bolstering the antioxidant defense system against reactive oxygen species	[137]
Date palm	350	Pot	2.5, 5 and 10 dS/m	Improved plant growth and alleviated salt-induced stress	[98]
Rice straw	550–600	Field	Saline water	Enhances the water-salt condition of the soil during saline irrigation, leading to an increase in winter wheat yield	[254]
Wheat straw	350–550	Field	Saline soil classified as solonchak	Improved the yield of both maize and barley	[212]
Grass and wood	450	Field	–	Improved carbon sequestration and increased tomato yield were observed in soil with an alkaline pH	[259]
Sunflower stalk pyrolyzed	400	Field	5 dS/m	Reduced soil EC, enhanced availability of soil nutrients, and a 47% increase in retained soil moisture collectively contributed to improved millet production	[217]
–	–	Pot	100 mM NaCl	Increased biomass, flowering rate, and photosynthetic efficiency in tomato plants	[205]
Pine wood chips	450	Pot	100 mM NaCl	Reduced oxidative damage, increased guaiacol peroxidase activity in tomato plants	[48]

Similarly, other studies have also investigated the effectiveness of biochar application in pot settings. El-Nahas et al. [62] conducted a study to assess the effects of irrigation water salinity (1500 and 3000 ppm) and different soil amendments (biochar, vinasses and humic acid) on sandy loam soil characteristics and wheat crop (*Triticum aestivum* L.) grain production. The incorporation of biochar led to significant improvement of yield. Additionally, in another controlled experiment, Khanam et al. [120] performed a pot experiment aimed at evaluating the impact of biochar on rice subjected to salt stress conditions. They observed that the application of 2, 4, and 6 t/ha of biochar led to the recovery of salt-induced damage caused by 1600 and 2800 ppm salt (NaCl) stress. Furthermore, this application extended the lifespan of rice plants by up to 80 days after transplanting, particularly under the 2800 ppm NaCl stress condition.

Moreover, Malik et al. [137] conducted a pot study to assess the physiological and biochemical performance of maize seedlings when subjected to either rice-straw biochar with alkaline pH and high EC (pH and EC of 9.65 and 5.3 dS/m) or humic acid, alone or in combination. Their results showed that the application of biochar and humic acid, whether individually or together, significantly mitigated the adverse effects of salinity on maize growth, antioxidative capacity and ion uptake. These amendments were found to enhance plant growth characteristics, physiological processes, ionic behaviour and antioxidant defenses, thus reducing the negative impacts of salinity-induced stress.

Additionally, Hussein et al. [98] investigated the effects of date palm-derived biochar (pH and EC of 8.84 and 0.163 dS/m) heated to 350 °C on the growth of Spinach (*Spinacia oleracea* L.) under various salt stress conditions from high to toxic (2.5, 5, and 10 dS/m) in potted research. The introduction of soil amendments using this biochar notably enhanced plant growth and alleviated the negative impacts of salt stress. Field tests have further shown the efficacy of biochar additions in raising agricultural production in saline environments, building on previous results from a controlled setting. In a different field experiment, for example, Zhang et al. [254] observed that using biochar (pH 9.48) made from rice straw that was pyrolyzed at moderate temperatures ranging from 550 to 600 °C in conjunction with straw mulching increased winter wheat output when irrigated with saline water. This combination has demonstrated enhanced water-salt characteristics of the soil, offering a beneficial method for growing winter wheat under such circumstances. To further explore this idea, Sun et al. [212] examined how growing maize and barley on coastal saline soil classified as solonchak was affected by biochar made from wheat straw from low to moderate temperature (350 and 550 °C). Their field test showed that soil treated with biochar produced more crops. In a field experiment, Zonayet et al. [259] evaluated the impact of grass and wood biochar pyrolyzed at moderate temperature of 450 °C as a soil conditioner for improving the characteristics of saline soil with sandy to clay loam texture, low OM content and slightly alkaline pH of 7.5 enhancing tomato productivity. They utilized biochar produced from grass and wood through pyrolysis at moderate temperature of 450 °C. Their findings indicated that biochar was most effective at carbon sequestration when the soil pH was alkaline, resulting in enhanced tomato yield. Yet, in another field experiment, Taheri et al. [217] conducted an experiment on clay-textured soil with alkaline pH of 8.05 with salinity problem (ECe of 9.1 dS/m). They explored the benefits of using sunflower stalk biochar pyrolyzed at moderate temperature of 400 °C and sulfur-modified biochar with characteristic high ECe of 6.74 and 6.81 dS/m. These amendments resulted in increased soil water content significantly by 47 and 35%, reduced soil EC and SAR, enhanced soil microbial and enzymatic activity and consequently, elevated soil-accessible nutrients and millet yield in comparison to the control conditions.

In the above various recent studies, the potential benefits of using biochar to address soil salinity and enhance plant growth have become known. These studies collectively emphasize the potential of biochar as a valuable tool in mitigating the challenges posed by soil salinity, enhancing soil quality and promoting sustainable agricultural practices.

The studies presented provided convincing evidence of biochar effectiveness in mitigating the crucial problem of soil salinity, which puts at risk agricultural productivity around the world. In addition to improving plant physiological processes like transpiration rates, ion uptake, antioxidative capacity and microbial activities, biochar also improves the properties of the soil because it prevents plants from the harmful effects of Cl^- and Na^+ ions, which are responsible for shifts in crop growth triggered by salinity stress [99]. The entire approach ensures that plants not only resist but flourish in saline conditions, significantly improving sustainable farming methods. Data presented shows that biochar can be positive in managing soil salinity. Biochar appears promising for increasing OM content and enhancing nutrient availability in the soil in addition to controlling the ratio of beneficial to toxic ions to support food security in salt-affected regions. Together, the outcome of this brief study postulates the importance of biochar in solving the problems related to salinity in the soil and providing farmers with a technique for better productivity in agriculture. Particularly for sensitive species, salinity and other abiotic factors significantly lower agricultural yields by causing water stress in plants and changing the soil nutritional balance [235]. Eco-friendly farming practices are currently recognized as the most promising means of reducing the problems brought on by salt. These methods focus on sustainable agriculture that does not harm the environment and averts the effects of climate change besides obtaining good yields without the use of fertilizer.

Methods of managing salt stress that are environmentally sound have been studied. Of these, the scientific community has focused a lot of emphasis on biochar since it is a sustainable way to lower soil salinity. Biochar also offers other benefits over and above decreasing soil salinity including enhancing soil fertility, sequestering heavy metals and carbon. The use of biochar has a positive effect on reducing the impacts of soil salinity on cultivated crops, according to recent studies covered here. This research includes both field and pot experiments carried out in naturally saline or artificially salinized soils. By increasing K availability, increasing salt sorption capacity, improving plant water intake and transpiration, decreasing soil EC, increasing soil accessible nutrients, optimizing water-salt balance, prolonging plant lifespan and improving crop performance, the application of biochar has been found to ameliorate soil salinity.

Biochar application can greatly alter soil EC. Biochar with AEC can immobilise soil salinity by removing excessive CI^- and SO_4^{2-}. More work must be done in regard to how the different types of biochar affects soil salinity, its effect on the soil EC and other biochar outcomes in the long run. This includes areas like crop type response, methods of using it and correct rate of biochar for maximizing soil health and crops yields.

It is also paramount to review the socio-economic viability and replicability of biochar application in the context of the biochar production cost, the availability of feedstock and the possible market value of the biochar products. Further research on the biochar should also embrace the possibility of interaction effects between the application of biochar and other soil management measures including drainage of the soil in a bid to enhance more on the reduction of salinity in the soil and improvement on the growth of crops.

13 Biochar, soil salinity and research focus/recommendation

Although a significant portion of the global population resides in developing nations, particularly Sub-Saharan Africa, which is increasingly vulnerable to salinity, numerous populations have been reported to be affected [113]. However, few sustainable biochar studies are directed towards addressing soil salinity, despite the proliferation of biochar initiatives in Africa,research endeavours by national institutes and universities are still limited and in nascent stages [121]. This constraint highlights a substantial research need that necessitates enhanced scientific investigation to adequately facilitate biochar application for salinity remediation throughout the continent. Furthermore, despite many African regions have a significant agricultural difficulty due to soil salinity, Africa has not yet profited from solutions designed to address its environmental and socio-economic circumstances.

Most biochar and salinity research has focused on other continents, resulting in a dearth of studies relevant to Africa. Because of this geographic disparity in research focus, there is an urgent need for studies that look at how biochar might lower soil salinity in African ecosystems and under African agricultural practices. It is more crucial than ever to prevent and reduce soil salinity in Africa, as the issue is still expanding and affects more than one billion hectares of land globally [87]. Ignoring this problem might eventually result in a catastrophe in the economy and public health [34].

In conclusion, even though biochar may be a sustainable input in managing soil salinity in African soils there remain numerous research questions that can still be investigated. Further study is required to comprehend its interactions with soil mineral composition, pH, OM and salt levels in more complex African ecosystems. These gaps can be filled by focused field studies and lab research, which will help develop more efficient, soil-specific biochar treatments that boost food security in regions with salinity problems, encourage sustainable soil management and increase agricultural production.

13.1 New developments in biochar for reducing soil salinity, challenges and prospects

Among the methods for reducing the impacts of salinity on crops, nanoparticles are becoming more well-known in the field of agriculture for their ability to increase crop tolerance to salinity [14]. Enhancing soil structure and quality, promoting plant growth and enhancing plant resistance to salt stress are the primary goals of nanoscale techniques [210].

Iron oxide nanoparticles (NPs) aid plants in combating salt stress by increasing water intake, increasing antioxidant content and maintaining ion levels [151]. Recent works reported that iron oxide NPs improve plant growth and production under salt stress conditions. When iron oxide NPs were applied to tomato plants grown in saline environments, the plants growth and photosynthesis was enhanced [1, 251] claim that the examined maize variety growth and production were significantly increased by the foliar spray application of iron oxide NPs. It was achieved by boosting photosynthetic pigments, encouraging the activity of antioxidant enzymes and raising K^+ and Ca^{2+} ion levels in both normal and salinity-stressed soils.

Increased Fe in plants treated with coated Fe-NPs decreased sodium, increased nitrogen, phosphorus, potassium iron and copper, preserved photosynthetic pigments and relative water content, and presented higher levels of key osmolytes like soluble sugars in shoots and lower levels of soluble sugars in root and proline in root and shoot. This ultimately alleviates the adverse effects of salt stress on Ajowan (*Trachyspermum ammi*) growth [146].

Using conventional techniques (such as nano-gypsum, nano-hydroxyapatite, nano-sulfur, etc.), nano-nutrients (such as Ca, Se, Si, ZnO, etc.), nano-amendments (such as nano-biochar, nano-compost, nano-chitosan, etc.), nano-halophytes and salt-tolerant genotypes are a few examples of these approaches [191].

In an attempt to improve soil and plant resistance to salt while lowering greenhouse gas emissions, biochar and its nanoscale counterpart, nano-biochar, have shown great potential [178]. Biochar has gained in widespread acceptance as a soil amendment due to its multiple benefits for soil fertility, nitrogen cycling and plant development (Sheikh

Table 8 Comparison between biochar and nano-biochar in terms of soil improvement

Factor	Biochar	Nano-biochar	References
Surface area	Lower surface area	Approximately 1.5 times higher surface area	[213]
Porosity	Less porous	More abundant pore structure	[213]
reactivity	Lower reactivity	Greater reactivity due to increased surface area and porosity	[192]
Water retention	Improves water retention	Enhances water retention capacity by 8.03% compared to bulk biochar	[213]
Nutrient leaching	Reduces NH_4^+-N leaching by 3.0–13.1% and NO_3^--N leaching by 2.7–3.6%	More effective in reducing NH_4^+-N leaching by 5.7–39.2% and NO_3^--N leaching by 9.0–43.3%	[213]
Soil infiltration	Decreases cumulative infiltration volume by 26.0–48.4%	Decreases cumulative infiltration volume by 14.1–62.4%	[213]
Soil microbial activity	Enhances microbial activity	Further enhances microbial activity and biodiversity, especially in contaminated soils	[133, 135]
Contaminant adsorption	Effective in immobilizing contaminants	Superior in adsorbing contaminants due to higher surface area and reactivity	[93, 192]
Soil structure	Improves soil structure	Significantly alters soil pore structure, increases soil porosity, and stability of soil aggregates	[43]
Environmental impact	Contributes to carbon sequestration	More effective in carbon sequestration and reducing greenhouse gas emissions	[115, 190]
Application rates	Typically applied at 1–20% (w/w)	Effective at lower application rates (e.g. 0.1–1.0% by mass)	[170, 257]
Potential risks	Generally considered safe	Potential environmental risks due to high mobility and reactivity, requiring further research	[112, 128]

et al. 2023). Nano-biochar is a modified type of biochar with nano-scale qualities, consisting of particles smaller than a micrometre (μm) and extending to the nanometre (nm) range [112]. The nanoscale decrease of biochar particle size enhances its SSA and CEC, which can improve its effectiveness as a soil amendment [115], resulting in improved soil structure and nutrient availability [43]. This may reduce the buildup of harmful ions in the rhizosphere, protect plants from the damaging effects of salinity stress and raise the negative charge and improve the adsorption of cations found in saline soil, such as Na^+ [134, 222].

Typically, conventional biochar has a larger particle size [59] and therefore lower SSA, and lower adsorption capacity compared to nano-biochar which had small particle size specifically between 1 and 100 nm making it to have higher SSA, greater adsorption capacity [210, 222] and improved mobility within the soil. These characteristics make nano-biochar more effective in nutrient retention and pollutant absorption [179, 190] than conventional biochar (Table 8). It also enhances soil pH, EC and CEC more effectively than conventional biochar [179, 190].

Biochar and nano-biochar use had demonstrated strategies for soil salinity mitigation. Both have been reported to increase salt resilience in plants, optimizing water and nutrient uptake, reducing oxidative damage, enhancing soil fertility and resilience [71, 73, 102, 103]. However, nano-biochar offers enhanced SSA, adsorption capacity, and mobility properties within soil, promoting soil properties, crop growth and environmental remediation [190]. Research on nano-biochar is still in its early stages [190], necessitating extensive investigation. But a recent study by Gill et al. [76] reported that nano-biochar significantly increases shoot and root biomass, chlorophyll content and antioxidant enzyme activities, leading to better plant resilience under salinity stress [76].

While both biochar and nano-biochar are valuable amendments for addressing soil salinity. The inherent nano-biochar properties such as larger surface area, higher adsorption capacity and greater mobility in the soil, allow it to interact more effectively with salt ions and the soil environment than conventional biochar. This results in a more defined and beneficial impact on plant growth and overall soil remediation. These suggest that nano-biochar enhanced properties translate into superior performance in mitigating soil salinity over conventional biochar despite nano-biochar research being in its early stages.

Despite their positive results, nanoparticles present some risks to soil ecosystems. Nanoparticles may undergo transformation and degradation steps such as dissolution in soil water, oxidation, photodegradation and passivation by coexisting substances or be absorbed by organisms, leading to their bioaccumulation which are able to reach lower water bodies and sediments [91]. These can directly and indirectly harm soil organisms, leading to disrupted soil structure and reduced fertility. Therefore, investigation into the fate of nanoparticles in soil ecosystems and their potential environmental toxicity are crucial for their safe use which remains an obvious research gap. According to Sultan et al. [210], both nano-biochar and biochar have been explored as potential tools for mitigating soil salinity, a significant achievement worldwide. However, their unique properties offer distinct advantages and drawbacks in this context of which are mentioned below:

13.2 Advantages of nano-biochar for soil salinity amelioration

- Due to the large surface area, nano-biochar enhances nutrient retention by reducing loss and leaching as indicated by Pathak et al. [163]. This assists in avoiding loss of nitrogen in the rhizosphere when the soil is saline.
- Improved soil structure [210]: Nano-biochar can improve the process of soil aggregation and water infiltration, and this decreases the concentration of salt at the root zone.
- Enhanced salt tolerance [244]: Using nano-biochar could enhance the ability of plants to tolerate salinity stress by reducing pressures on plant cells in terms of oxidative stress and increasing their antioxidant capacity.

13.3 Drawbacks and problems of using nano-biochar to improve soil salinity

- Higher production costs [29]: Because nano-biochar is frequently more expensive to create than normal biochar, its widespread application in salt-prone areas may be limited.
- Limited availability (eg., [163]): Because nano-biochar is a relatively new technology, little is known about its creation and stability in addressing soil salinity (e.g., [163]).
- Potential environmental impacts: Xiang et al. [233] stated that the production and use of nano-biochar can affect the environment in terms of the release of the nanoparticles.
- Limited research (eg., [194]): limited results are available about the impact of nano-biochar addition in the soil–plant system.

13.4 Benefits of using biochar to reduce soil salinity

- Traditional techniques, which are frequently less expensive than nano-biochar, allow farmers in regions affected by soil salinity to generate biochar more easily.
- Wide availability: Biochar may be produced from a wide range of biomass sources, making it available everywhere.
- Enhance soil structure: Jeffery et al. [110] notes that biochar enhances the physical characteristics of the soils and its water holding capacities thereby lowering the risk of salinity at the root zone.
- Carbon sequestration: Biochar enhances soil fertility since it stores carbon in the soils while at the same time combating climate change.

13.5 Limitation/ drawbacks of biochar for ameliorating soil salinity

- Relatively smaller surface area: Biochar had surface area lower than that of nano-biochar which might restrict its capacity to adsorb and hold onto nutrients [21].
- Nutrient leaching: When leaching is used to remove salt from saline soils, biochar may occasionally accelerate nutrient leaching [126].
- Limited study evidence: To completely comprehend the long-term impacts of biochar on soil salinity and plant development, more investigation is required especially long-time field research.

Both biochar and nano-biochar have the ability to reduce soil salinity. Although nano-biochar has the potential to increase plant salt tolerance and nutrient retention. Its limited availability and high cost may impede broad use. Despite being more readily available and less expensive, conventional biochar may be less effective in retaining nutrients and may result in nutrient loss. Long-term agricultural objectives, resource limitations and soil properties will all influence the best option.

13.6 Future recommendations/directions for nano-biochar and biochar in soil salinity amelioration

There are potential advantages and challenges in the use of biochar and nano-biochar, a number of research approaches might be considered to advance and broaden the use of nano-biochar and biochar for soil salinity remediation.

13.6.1 Nano-biochar

- Production optimization: More focused study in this area could be carried out in the development and identification of improved and cheaper techniques for synthesizing nano-biochar for saline soils.
- Surface modification: Examining the impact of changing the physicochemical characteristics of nano-biochar to increase its capacity to adsorb salt and reduce nutrient leaching.
- Synergistic interactions: To understand how nano-biochar enhances the improvement of general soil qualities when combined with gypsum or other materials.

- Long-term field trials: Carrying out a trial investigation in a field with different salinity settings to establish the long-term gains and losses of employing nano-biochar.
- Environmental risk assessment: Ascertaining the risks that the usage of nano-biochar can have on the local edaphic condition, water status and overall biogeochemistry.

13.6.2 Biochar

- Functionalization: Exploring the mechanisms of surface chemistry to alter the properties of the biochar to increase the adsorption of salt and decrease nutrient leaching.
- Integration with sustainable agricultural practices: Investigating the effects of biochar as a soil amendment on improving tolerance to salinity and other approaches to farming such as precision and organic farming.
- Cost-effective production methods: Identifying improved processes of producing biochar using various feedstocks with improved efficiency and resource use.
- Long-term field trials: Establishing a series of field trials to establish the performance and drawbacks of applying biochar in saline environments in the long run.

13.7 Collaborative research

We can fully utilize the potential of biochar and nano-biochar as an innovative and environmentally friendly practice to address the issues of salinity and foster increased yields of crops within affected states by these approaches:

- Interdisciplinary collaboration: Encouraging collaboration between researchers from various fields, including soil science, agricultural engineering, environmental science and material science.
- Public–private partnerships: To increase the cooperation between governments, private companies and research institutions work together to develop and market biochar and nano-biochar to reduce soil salinity.
- Knowledge sharing and dissemination: Promoting the exchange of experience and research outcomes through publications and conferences, as well as on social media.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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