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Biochar Application for Reducing Soil Salinity and Promoting Plant Growth under Climate Change

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Abstract

Soils affected by salinity, which substantially limit agricultural productivity, are becoming an increasingly serious concern due to climate change and unsustainable land management practices. Biochar, a stable, carbon-rich material derived from biomass, has shown significant potential for mitigating the negative impacts of soil salinization. This paper examines the role of biochar in enhancing soil properties, promoting plant growth, and alleviating salinity stress. Evidence indicates that biochar improves key soil physical characteristics, including aggregate stability, porosity, and water-holding capacity, while also enhancing nutrient availability and cation exchange capacity. Moreover, biochar positively influences soil microbial communities, thereby strengthening soil health and increasing plant resilience to salt stress. Studies demonstrate that biochar can boost crop yields by an average of 29.3% through improving plant tolerance to saline conditions. This enhancement is linked to biochar's ability to improve soil structure, facilitate nutrient cycling, and reduce toxic ion concentrations. Additionally, biochar contributes to climate change mitigation by sequestering carbon in soils and lowering greenhouse gas emissions. Nonetheless, potential drawbacks, such as the presence of toxic compounds or free radicals, must be carefully considered. This review highlights the importance of optimizing biochar production processes, including the choice of feedstocks (such as agricultural residues, organic waste, or halophytes) and particle size. It also identifies research gaps and suggests future directions, including the development of "carbon-neutral" or "carbon-negative" biochar systems through advanced pyrolysis or gasification techniques that minimize greenhouse gas emissions, promote sustainable agriculture, and support food security in salt-affected regions.

Keywords

Biochar, Salt-Affected Soils, Soil Remediation, Crop Productivity, Salinity Stress

1. Introduction

Soil salinization is a form of land degradation characterized by the excessive buildup of soluble salts in the soil. In cases of naturally occurring (primary) salinization, salt buildup typically originates from sources such as rainfall containing oceanic salts (wet deposition), wind-driven transport of salt particles (dry deposition), and the physical or chemical weathering of parent rock materials. Salts can also be mobilized from saline geological formations through surface runoff or shallow groundwater movement. In contrast, secondary or anthropogenic salinization is primarily driven by human activities. These include the use of saline or brackish water for irrigation, inadequate water and land management practices leading to elevated water tables, seawater intrusion into coastal aquifers often a result of rising sea levels or over-extraction of freshwater and the excessive application of fertilizers [1]. Projections estimate that the global population will rise from approximately 7 billion to between 9 and 10 billion by 2050, necessitating an estimated 60% to 110% increase in food production to ensure food security [2]. Anthropogenic activities such as deforestation and the intensive consumption of fossil fuels have led to a significant rise in atmospheric CO_2 concentrations, increasing from pre-industrial levels of approximately 280 ppm to over 400 ppm. Projections indicate that these levels may reach up to 800 ppm by the end of the 21st century [3]. According to the Food and Agriculture Organization (FAO), over 1.4 billion hectares of land, approximately 10% of the global total are affected by salinity, with another billion hectares at risk due to climate change and unsustainable land practices. This was highlighted in FAO's first major global report on salt-affected soils in 50 years, presented at the 2024 International Soil and Water Forum in Bangkok. FAO warns that rising soil salinity severely reduces fertility and threatens food security, with crop yield losses of up to 70% reported in some regions. The report estimates that 10% of irrigated and rainfed cropland is already impacted, and models suggest that, if current climate trends continue, salt-affected areas could expand to cover 24% - 32% of the Earth's surface, particularly in developing countries. Ten countries, including China, the United States, and Iran, account for 70% of the world's salt-affected soils [4]. The GSASmap illustrates the global distribution of salt-affected soils (SAS) with electrical conductivity of the extract (ECe) greater than 2 dS/m, exchangeable sodium percentage (ESP) higher than 15 percent, and pH levels above 8.2. This assessment is provided for two soil depth ranges, from 0 to 30 centimeters and from 30 to 100 centimeters. Based on current data collected from 118 countries, which together represent about 85% of the Earth's land surface, it is estimated that more than 424 million hectares of topsoil within the 0 to 30 centimeter layer and approximately 833 million hectares of subsoil in the 30 to 100 centimeter layer are affected by salinity. In the topsoil layer, 85% of salt-affected areas are saline, 10% are sodic, and 5% are saline-sodic. In the subsoil, 62% of affected areas are saline, 24% are sodic, and 14% are saline-sodic (FAO, 2021) [5].

Salt-affected soils are generally classified into three main types: saline soils, saline-sodic soils, and sodic soils. Saline soils are identified by an electrical conductivity of the saturated soil extract (ECe) greater than 4 dS/m at 25˚C, a pH typically below 8.5, and an exchangeable sodium percentage (ESP) less than 15. Saline-sodic soils also have an ECe exceeding 4 dS/m at 25˚C, but their ESP is above 15. The pH of these soils can be either below or above 8.5. The high sodium content in these soils often leads to the breakdown of soil structure, which negatively affects plant development. In contrast, sodic soils are characterized by an ESP greater than 15 and an ECe below 4 dS/m at 25˚C. The pH in these soils usually falls between 8.5 and 10. Due to the high sodium levels and low salinity, soil particles tend to disperse, which reduces soil permeability and hampers water movement through the profile [6].

Elevated soil salinity can result from human activities, particularly due to improper fertilization and inefficient water management. Naturally saline soil is also common, especially in arid and semi-arid areas with low rainfall [7].

Soils with poor physicochemical and biological properties hinder plant growth, often due to natural processes, agricultural practices, or pollution. Biochar, a multifunctional carbon material, has been shown to improve soil quality and crop productivity, particularly in saline-sodic soils. This review highlights the positive effects of biochar on soil properties, microbial activity, and rice growth under salinity conditions, emphasizing its potential to enhance soil remediation and rice production [8]. Salinity is a major stressor that negatively impacts global crop production, but biochar, as an activated carbon soil conditioner, has the potential to alleviate its effects. Soil salinity is a growing concern, especially in arid and semi-arid regions, and this study aimed to assess the potential of biochar in alleviating salt stress in tomatoes (*Solanum lycopersicum*) [9].

Abiotic stressors like drought and salinity severely impact crop yields, posing a significant threat to global food security, which is exacerbated by climate change. Utilizing agricultural waste to produce biochar offers an eco-friendly and sustainable solution to mitigate these stresses, ultimately supporting food production. This study explores the processes involved in biochar production from agro-waste, its role in improving soil properties, and its ability to enhance plant resilience against drought and salinity by boosting water retention, nutrient balance, and antioxidant activities, thereby ensuring sustainable crop yields under harsh conditions [10].

2. Abiotic Stress in Plants

Abiotic stress represents a major constraint on global crop productivity and contributes to the reduction of arable land. This issue is becoming increasingly critical in the context of rapid population growth and ongoing climate change. Abiotic stresses like drought and salinity pose significant threats to food security. Godoy *et al.* (2021) [11] conducted a comprehensive review of existing literature on the use of various natural plant metabolites, both primary (such as proline, L-tryptophan, glutathione, and citric acid) and secondary (including polyols, ascorbic acid, lipoic acid, glycine betaine, α-tocopherol, and melatonin) to enhance plant tolerance to abiotic stress. Their analysis focused on key environmental stressors such as drought, salinity, heavy metals, and temperature fluctuations, which are anticipated to intensify in frequency and severity due to ongoing climate change. The effectiveness of these compounds is typically assessed through their influence on metabolic, biochemical, and morphological traits across multiple crop species, with many studies reporting improved yields under both greenhouse and field conditions. Given the demonstrated potential of this approach to strengthen plant resilience, the feasibility of its broader application in the near future is also explored. Plants frequently encounter various forms of abiotic stress (**Figure 1**), including ultraviolet radiation, elevated temperatures, drought, salinity, and heavy metal exposure. These stressors disrupt the balance between pro-oxidant and antioxidant molecules, leading to a condition known as oxidative stress [12].

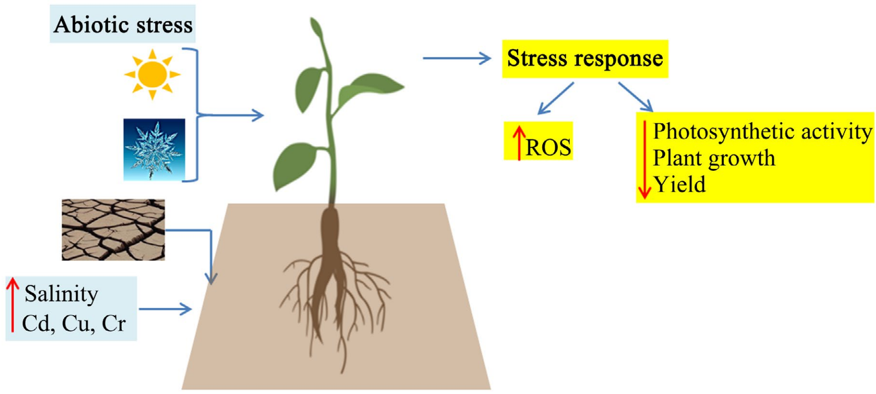

Figure 1. Impact of abiotic stress on crop productivity. Environmental stressors including extreme temperatures, drought, salinity, and heavy metal exposure (e.g., cadmium, copper, chromium) trigger physiological and biochemical responses in plants, such as elevated reactive oxygen species (ROS) production and decreased photosynthetic efficiency leading to inhibited growth and reduced agricultural yields.

Abiotic stress enhances the activity of the photorespiratory pathway, resulting in increased production of hydrogen peroxide (H_2O_2). Additionally, reduced carbon dioxide uptake and assimilation disturb the electron flow within the photosynthetic electron transport chain, which in turn promotes the generation of reactive oxygen species such as superoxide radicals and singlet oxygen ($^1O_2$). Alongside hydroxyl radicals (·OH), the accumulation of H_2O_2, superoxide, and $^1O_2$ causes oxidative damage to proteins, lipids, and nucleic acids, ultimately contributing to cellular injury and death [13].

To mitigate oxidative stress, plants rely on both enzymatic and non-enzymatic antioxidant defenses. The enzymatic system comprises several key enzymes responsible for scavenging reactive oxygen species (ROS), including superoxide dismutase (SOD), catalase (CAT), monodehydroascorbate reductase (MDHAR), dehydroascorbate reductase (DHAR), glutathione reductase (GR), glutathione transferase (GST), ascorbate peroxidase (APX), glutathione peroxidase (GPX), and guaiacol peroxidases (POXs). The activity of these enzymes is typically upregulated under stress conditions. Complementing this, the non-enzymatic defense involves the synthesis of antioxidants such as proline, glutathione (GSH), ascorbic acid, carotenoids, flavonoids, and tocopherols, which help neutralize ROS and reduce oxidative damage [14].

2.1. Salinity as an Abiotic Stress and Its Induction of Oxidative and Physiological Responses

Salinity stress is one of the most pervasive forms of abiotic stress affecting plants, imposing both osmotic and ionic challenges that ultimately trigger oxidative damage and physiological dysfunction. Elevated salt concentrations in the rhizosphere reduce soil water potential, making water uptake more difficult and causing osmotic stress. This results in reduced cell turgor, stomatal closure, and diminished CO_2 assimilation, which limits photosynthetic activity. The consequent over-reduction of the photosynthetic electron transport chain promotes the leakage of electrons to oxygen, leading to excessive generation of reactive oxygen species (ROS) such as superoxide, hydrogen peroxide, hydroxyl radicals, and singlet oxygen [15] [16]. In parallel, ionic stress arises from the excessive accumulation of Na^+ and Cl^- in plant tissues, which disrupts nutrient balance, particularly the uptake and homeostasis of K^+ and interferes with enzymatic activities, protein stability, and membrane integrity [17] [18]. These ionic perturbations exacerbate oxidative stress by impairing chloroplast and mitochondrial metabolism, further enhancing ROS production [19]. ROS are not only damaging agents but also function as signaling molecules regulating stress responses. However, under salinity, ROS often accumulate beyond the scavenging capacity of the antioxidant machinery, leading to oxidative damage manifested as lipid peroxidation, protein oxidation, DNA damage, and disruption of cellular organelles [20]. Physiologically, these processes are reflected in reduced growth, membrane instability, inhibition of photosynthesis, and overall yield loss [21]. To counteract salinity-induced oxidative stress, plants activate both enzymatic (e.g., superoxide dismutase, catalase, ascorbate peroxidase, glutathione reductase) and non-enzymatic (ascorbate, glutathione, flavonoids, carotenoids) antioxidant systems. They also accumulate osmoprotectants such as proline and glycine betaine to stabilize proteins and membranes, maintain osmotic balance, and protect the photosynthetic apparatus [16] [21]. Additionally, plants employ ion compartmentalization and selective ion transport to sustain a favorable K^+/Na^+ ratio, alongside stress-responsive hormonal signaling pathways (e.g., ABA) to regulate stomatal conductance and gene expression [18]. Together, these responses illustrate the direct link between salinity as an abiotic stress and the cascade of oxidative and physiological disturbances it induces, highlighting the complexity of plant adaptive mechanisms under salt stress.

2.2. Effects of Drought and Salinity Stress on Plant Growth and Development

Drought stress (DS) and salinity stress (SS) are significant abiotic stresses that severely impact crop productivity worldwide and their effects have been exacerbated by rapid climate change, threatening global food security. Drought stress is induced by inadequate water availability, leading to a series of molecular, biochemical, and physiological modifications that enable plants to adapt to water deficit conditions. The variability and unpredictability of drought events are influenced by multiple factors, including the water retention capacity of the rhizosphere, rates of evapotranspiration, and irregular, uneven precipitation patterns. Water constitutes a substantial proportion of plant canopy biomass and is integral to various physiological processes essential for plant metabolism, growth, and development. Consequently, periods of water scarcity, particularly during dry seasons, represent critical stress phases that can severely impede plant growth, especially in drought-prone regions. The impact of drought stress on crop development is contingent upon the severity of the stress, the species involved, and the specific growth stage at which the stress occurs. Drought stress adversely affects virtually all aspects of plant metabolism, manifesting in alterations to morphological, physiological, biochemical, and molecular parameters. The subsequent sections provide a comprehensive examination of the effects of drought stress on plant systems [22]. Soil health, a key component of the "One Health" initiative and the Sustainable Development Goals (SDGs), faces serious challenges from salinization and sodification caused by both environmental processes and human activities [23]. Soil health is essential for crop productivity, but degradation from salinity, particularly in saline-sodic soils, limits plant growth through osmotic stress, ion toxicity (e.g., Na^+, Cl^-), and nutrient imbalances. Soil acidity and salinity are major challenges for agriculture, impacting soil health and crop productivity. Salinity stress is a significant issue in arid and semi-arid regions, such as the southern high plains of the U.S., where salt accumulation in the root zone negatively impacts plant growth and yield.

3. Biochar

Biochar offers numerous agricultural and environmental benefits, such as enhancing soil health, improving crop growth and yield, and mitigating greenhouse gas emissions. It transforms soil properties, promotes seed germination, boosts plant resistance to stresses, and improves nutrient cycling, though its effectiveness depends on factors like feedstock, pyrolysis temperature, and application method [24].

Biochar is characterized by its high carbon content, abundance of functional groups, strong alkalinity, notable porosity, and substantial specific surface area (SSA). Due to these properties, it has been extensively applied as an organic amendment in acidic and neutral soils to enhance soil fertility. Nonetheless, the specific effects of biochar on saline soil properties and the underlying mechanisms remain insufficiently understood. Consequently, this study aims to evaluate how biochar influences the physical, chemical, and biological attributes of saline soils. The findings indicate that biochar can: 1) Reduce soil bulk density, increase porosity, support soil aggregate formation, and facilitate salt leaching; 2) Enhance soil cation exchange capacity (CEC) and reduce salinity through ion exchange and adsorption mechanisms; 3) Serve as a direct nutrient source, aid in nutrient and water retention, and improve nutrient dynamics, including soil organic carbon (SOC) turnover and nutrient cycling; 4) Promote the diversity and functionality of soil microbial communities, thereby indirectly influencing carbon, nitrogen, and phosphorus cycling processes. However, these effects are significantly influenced by the biochar's characteristics, its application rate, as well as the specific soil type and environmental context [25].

In a recent comprehensive systematic review and meta-analysis, Wang *et al.* (2024) [26] synthesized findings from 660 paired observations across 99 peer-reviewed studies to assess the impact of biochar application on salt-affected soils. Their analysis focused on identifying the key determinants of biochar effectiveness, including initial soil characteristics, biochar properties, and various experimental conditions. The meta-analysis revealed that biochar significantly improved saline soil conditions, notably reducing the electrical conductivity of the saturated paste extract (ECe) by an average of 13.2%. This reduction was particularly pronounced in soils experiencing severe salinization, while lesser effects were observed in soils with mild to moderate salinity. Additionally, biochar application led to a notable 17.0% increase in soil cation exchange capacity (CEC), indicating improved nutrient retention capacity. Conversely, no statistically significant changes were detected in soil pH following biochar amendment. Biochar (BC), produced through pyrolysis of various biomass materials, is a powerful soil amendment whose effectiveness depends on the pyrolysis temperature and feedstock type. Biochar produced at temperatures above 500˚C increases soil bulk density and porosity, while biochar produced at lower temperatures (<500˚C) enhances bacterial diversity [27]. When applied to soil, biochar improves its physical and chemical properties, such as porosity, moisture retention, and nutrient availability, while reducing the negative impacts of salt, drought, and contamination, ultimately supporting agricultural sustainability, especially in semi-arid and arid regions [28]. Biochar, produced through the pyrolysis of organic materials, enhances soil fertility by improving its cation exchange capacity (CEC) and water-holding capacity, thereby boosting nutrient availability [29] [30]. The properties of biochar vary depending on the feedstock used and the pyrolysis temperature. When added to saline soils, biochar improves key physicochemical parameters, such as organic carbon, CEC, and available phosphorus, while also enhancing enzymatic activity, which ultimately supports increased crop productivity [31]. Biochar produced by pyrolysis biomass at 300˚C - 1000˚C has shown promise in reclaiming salt-affected soils by reducing electrical conductivity (ECe), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR), while improving soil structure, water infiltration, pH, and nutrient availability [32] [33].

3.1. Chemical Composition and Physical-Chemical Properties of Biochar

A study investigated the effects of biochar as a soil amendment on quinoa growth, physiology, and yield under both independent and combined drought and salinity stress. Results showed that biochar significantly mitigated the negative impacts of these stresses, improving plant height, shoot biomass, and grain yield, especially when combined with alternate root-zone drying irrigation (ARD) under salinity, suggesting biochar as a promising approach for improving crop productivity in stressed environments. The study utilized biochar derived from corn straw pyrolyzed at 500˚C under anaerobic conditions. The resulting biochar was alkaline, with a particle size of 1.5 - 2 mm. Its composition included 70.38% carbon, 1.53% nitrogen, 1.68% hydrogen, 0.78% sulfur, and 31.8% ash, with a cation exchange capacity of 12.0 cmol(+)/kg, electrical conductivity of 1.05 mS/cm, and a pH of 9.14 [34]. Tang *et al.* (2023) [35] reported similar characteristics in their biochar samples ranging in size from 1.0 to 2.0 mm. The biochar had a pH of 9.0 and an electrical conductivity (EC) of 0.83 mS/cm. Their findings showed that the physicochemical properties of biochar varied depending on particle size. While pH remained relatively constant between 9.0 and 9.5 across different particle sizes, EC showed significant variation: smaller particles exhibited higher EC than the soil, whereas larger particles had lower EC values compared to the soil. The soil used in the study was premium topsoil sourced from LessMess Soil (Concord, ON, Canada), a common urban soil composed of mineral materials derived from calcareous subsoil. Its properties included a total carbon content of 26.4% and total nitrogen of 1.06%, both measured using Dumas combustion. Extractable phosphorus was 130 mg/L (determined using sodium bicarbonate extraction), magnesium was 480 mg/L, and potassium was 2500 mg/L (both extracted using ammonium acetate). The biochar was produced by Burt's Greenhouses (Odessa, ON, Canada) from waste mixed-wood shipping pallets using a BlueFlame boiler in pyrolysis mode at 700˚C for 30 minutes. The total carbon content of the resulting biochar was 64.5%, as determined by Dumas combustion analysis performed by Activation Laboratories Ltd. (Ancaster, ON, Canada). These findings highlight the importance of optimizing biochar particle size for improving plant responses, particularly in saline soils. Biochar application on coastal saline soil for climate change mitigation, focusing on soil organic carbon (SOC), and greenhouse gases (GHGs), and crop yields has been investigated by Lin *et al.* 2015 [36]. Biochar was applied at 16 $t \cdot ha^{-1}$, which resulted in a 27.7% increase in wheat grain mass per plant and enhanced SOC, while not influencing non-biochar SOC. The results indicated that biochar sequestered 92.3% of its carbon into the soil within one year, with no significant effect on GHG emissions, and demonstrated a greater global warming mitigation potential compared to corn stalk application [36].

3.2. Biochar Mechanisms and Effectiveness across Different Types of Salt-Affected Soils

Mechanisms and effectiveness differ significantly depending on soil type. In saline soils, biochar improves plant growth primarily by adsorbing excess salts, enhancing soil porosity, and providing a conducive habitat for beneficial microbes, which in turn help reduce osmotic stress and ionic toxicity [37]. In sodic soils, where dispersion and poor structure are the dominant constraints, biochar plays a different role. Its carbonaceous particles and associated cations (especially Ca^{2+}, Mg^{2+}, and K^+ released from biochar ash) help reduce exchangeable sodium percentage and promote flocculation, thereby improving soil aggregation, hydraulic conductivity, and aeration [38]. Furthermore, the alkaline nature of many biochars can buffer soil pH, mitigating the extreme alkalinity often associated with sodicity [39]. Saline-sodic soils, due to the combination of both osmotic and dispersive stresses, often require dual mechanisms of remediation. Here, biochar effectiveness tends to depend on its feedstock and production temperature. For instance, high-ash biochars (e.g., from crop residues or manure) have been shown to provide both salt adsorption capacity and cation release for Na^+ displacement, making them more effective than low-ash woody biochars [40] [41]. However, the improvement in soil structure and reduction in salt stress in saline–sodic soils are usually slower and less pronounced compared to their effects in solely saline or sodic soils, highlighting the need for integrated strategies (e.g., combining biochar with gypsum or organic compost) [42]. Overall, while biochar universally improves soil organic carbon content, microbial activity, and nutrient cycling across salt-affected soils, the dominant mechanisms of action—ion adsorption, cation exchange, pH buffering, or structural improvement are strongly soil-type dependent. Tailoring biochar properties (e.g., feedstock selection, pyrolysis temperature, particle size) to match the constraints of specific salt-affected soils is therefore essential for maximizing its remediation potential.

3.3. Harnessing Biochar to Mitigate Abiotic Stress in Plants

To combat abiotic stress challenges, various strategies are being employed, with biochar (BC) emerging as a widely used soil amendment that can improve soil health and enhance crop yield under stress conditions. Soil salinization negatively impacts crop productivity and biochar has emerged as a potential solution to mitigate its harmful effects. Biochar, a carbon-rich material derived from biomass, has gained attention as a potentially effective yet inconsistently performing strategy for improving the physical, chemical, and biological conditions of salt-affected soils. While research on biochar is expanding, especially in relation to soil restoration and climate mitigation, further in-depth analysis is needed to clarify its mechanisms, particularly its effects on soil biology and to advance related technologies. To address food security, sustainable strategies for reclaiming and utilizing salt-affected soils are essential. BC enhances soil organic matter, structure, aggregate stability, and nutrient and water retention capacity, while also promoting the activity of beneficial microbes, which collectively help plants better tolerate these stresses. BC also protects membrane stability, enhances water uptake, balances nutrients, reduces reactive oxygen species (ROS), and improves photosynthetic activity, chlorophyll synthesis, and stress-responsive protein activity. This review explores the mechanisms through which BC mitigates drought and salinity stresses in plants and provides insights into how BC can be effectively used to improve stress tolerance in crops [43].

Biochar has shown promise in mitigating these issues by improving soil pH, nutrient uptake, microbial activity, and reducing toxic ion concentrations [44]. By improving nutrient and water uptake, reducing electrolyte leakage, and enhancing antioxidant activity, biochar helps plants counter osmotic, ionic, and oxidative damages caused by salinity stress. Additionally, biochar enhances soil organic matter, microbial activity, and reduces the accumulation of toxic ions, making it a promising tool for alleviating salinity stress and improving plant growth. Under saline conditions, Na^+ uptake increases and disrupts nutrient balance, but biochar reduces Na^+ absorption, enhancing K^+ uptake and improving the K^+/Na^+ ratio. Its high surface area, porosity, and cation exchange capacity help displace Na^+ from soil exchange sites, increasing the availability of beneficial nutrients like K, Ca, and Mg. Biochar also slightly raises soil EC, aiding nutrient release and supporting better plant growth under salinity stress [45].

A greenhouse pot experiment assessed the effects of salinity stress on eggplant growth and yield, as well as the potential of hardwood and softwood biochar to mitigate these effects. The results indicated that biochar improved plant physiology, root and shoot growth, and yield under salinity stress, with no significant difference between the two types of biochar [46]. Biochar application enhances soil carbon sequestration, permeability, fertility, and microbial activity, thereby increasing water retention and nutrient availability, which collectively promote improved plant growth [47]. Zhang *et al.* (2020) investigate the interactive effects of drought and salinity stress on soybean growth and productivity, focusing on the role of biochar as a mitigating factor [48].

A pot experiment was conducted to assess soybean yield, leaf gas exchange, and water use efficiency (WUE) under these stress conditions with and without biochar amendment. Results showed that both drought and salinity stress significantly reduced soybean growth, flowering time, and leaf gas exchange parameters, with salinity stress causing notable declines in photosynthesis, stomatal conductance, CO_2 concentration, and transpiration. Biochar application improved soybean grain yield by 3.1% - 14.8% and enhanced WUE under drought stress, while reducing the negative effects of salinity stress. The study concluded that biochar can effectively alleviate the detrimental impacts of combined drought and salinity stress on soybean growth and productivity, highlighting its potential in sustainable agricultural practices. This study explored the impact of biochar on the growth and productivity of *Solanum lycopersicum* (tomato) under drought and saline stresses in greenhouse conditions [49]. A three-factorial split-split-plot design was used, with variables including water quality (freshwater vs saline water), irrigation levels (40%, 60%, 80%, and 100% of total evapotranspiration), and biochar application (3% by weight). The results revealed that drought and salt stresses negatively affected the plant's morphological, physiological, and yield characteristics, particularly under low irrigation levels. However, the addition of biochar significantly improved plant height, stem diameter, leaf area, water use efficiency, and tomato yield. Biochar enhanced growth parameters, physiological characteristics, and yield, with the highest improvements in yield observed under freshwater irrigation. This study suggests that biochar application can enhance tomato growth and yield while improving water use efficiency in semi-arid and arid regions.

Another group of researchers has also done greenhouse experiment to assess the effect of biochar amendments on the productivity of tomatoes grown in salt-affected soils. The study, conducted over two growing seasons, tested four biochar application rates (0%, 2%, 4%, and 8% by mass) under saline irrigation conditions. Results showed that saline irrigation significantly reduced tomato yield and quality, but biochar amendments improved vegetative growth, yield, and quality, with the highest biochar rate (8%) providing the most significant benefits. Biochar mitigated salt stress by adsorbing sodium ions and releasing essential nutrients like potassium, calcium, and magnesium into the soil, thereby enhancing tomato production [50].

Salt stress is a major abiotic factor that limits crop production globally, with wheat being one of the most affected crops. This study aimed to investigate the ameliorative effects of biochar on wheat (*Triticum aestivum L.*) grown under saline conditions. The wheat varieties FSD08 and PUNJAB-11 were subjected to two levels of sodium chloride (0 mM and 120 mM), along with biochar application at 0% and 5%. Results showed that salt stress negatively impacted wheat growth, yield, and physiological attributes, while biochar significantly improved plant performance by enhancing antioxidant enzyme activities (SOD, CAT, APX, and POD), reducing membrane permeability, and decreasing harmful ion concentrations. Biochar effectively mitigated the detrimental effects of salinity, suggesting its potential as a sustainable solution for crop production in saline environments [51]. Between 2000 and 2019, the frequency of extreme weather events like droughts and floods increased by over 75%, compared to 1980-1999, driven by climate change, resulting in significant deterioration of soil and water quality. At the same time, the growing human population has placed additional pressure on soil and water resources due to overuse and mismanagement. This review explores the damage caused to soil-plant systems by extreme weather events and discusses how biochar, with its beneficial properties such as high cation exchange capacity, water retention, and nutrient holding capacity, can help restore the damaged systems. Biochar has the potential to improve soil fertility, enhance crop productivity, and mitigate greenhouse gas emissions, offering a sustainable solution for areas affected by extreme weather. The paper also suggests future strategies to promote biochar's use in mitigating the adverse effects of extreme weather on soil-plant systems [52].

Salt-affected soils require urgent remediation to achieve carbon neutrality and ensure food security. Limited reviews are available on the role of biochar in remediating salt-affected soils, particularly in the context of carbon neutrality and climate change mitigation. This review highlights two pathways for achieving carbon neutrality while remediating salt-affected soils using biochar: 1) producing biochar from sustainable feedstocks via thermal technologies and 2) applying biochar to enhance plant productivity and mitigate greenhouse gas (GHG) emissions. Converting biomass waste into biochar can help reduce GHG emissions and facilitate carbon dioxide removal (CDR), with the collection of halophyte biomass as biochar feedstock and the development of biochar poly-generation production systems being promising strategies. Biochar has been shown to improve plant growth in salt-affected soils by enhancing physicochemical characteristics, shifting microbial communities, and boosting plant halotolerance, with an average increase in plant productivity of 29.3%. Additionally, biochar can mitigate GHG emissions by inducing negative priming effects, improving soil properties, and altering microbial communities related to carbon and nitrogen cycles. However, biochar may also have negative effects on plant growth due to the presence of toxic compounds and free radicals, which can deteriorate soil properties. Promoted GHG emissions are mainly attributed to positive priming effects and the release of labile carbon and inorganic nitrogen fractions as microbial substrates. This review identifies gaps in current research and outlines future directions, such as the development of "carbon-neutral" or "carbon-negative" biochar production systems, balancing biochar's effectiveness with its environmental risks and costs, and designing biochar-based GHG adsorbents to remediate salt-affected soils, achieve carbon neutrality, and help mitigate climate change [53].

The application of 5% and 10% biochar under saline conditions enhanced plant growth, improving parameters like plant height, leaf area, and fresh and dry weight, with the 10% biochar dose showing the most significant improvements. Biochar also reduced oxidative and osmotic stresses by decreasing the activities of key enzymes and stress markers, making it a promising strategy for mitigating salinity effects on tomato seedlings [9].

Yuan *et al.* 2023 [54] reviewed the role of biochar in enhancing salt-affected soil health, highlighting its ability to improve soil properties such as aggregate stability (15.0% - 34.9%), porosity (8.9%), water retention capacity (7.8% - 18.2%), cation exchange capacity (21.1%), soil organic carbon (63.1%), and nutrient availability (31.3% - 39.9%), while also reducing bulk density (6.0%) and alleviating salt stress (4.1% - 40.0%). Biochar also benefits soil biology by increasing microbial biomass (7.1% - 25.8%), stimulating enzyme activity (20.2% - 68.9%), and promoting plant growth. To better assess the health of salt-affected soils, it is crucial to use indicators that reflect ecological services, such as plant productivity, water quality, climate change mitigation, and human health. This approach will improve soil health evaluation and provide a more comprehensive understanding of soil multifunctionality.

Ud Din *et al.* (2023) [55] evaluated the effects of compost and biochar amendments on tomato growth and fruit quality under salinity stress, showing that both amendments significantly improved plant growth, reduced sodium accumulation, and mitigated salinity-induced physiological stress. The combined application of compost and biochar notably enhanced tomato plant growth, alleviated salinity toxicity, and improved productivity, making it a promising approach for cultivating crops in saline soils.

Kanwal *et al.* (2018) [56] evaluated the impact of 1% and 2% biochar on wheat seed germination and growth under salinity stress, finding that both levels improved germination and growth, with 2% biochar being more effective. The 2% biochar treatment led to increased root and shoot length, improved leaf water and osmotic potential, and a reduction in proline and soluble sugar content, ultimately enhancing wheat productivity under saline conditions.

Economic Feasibility of Biochar Application in Salt-Affected Regions

While biochar demonstrates clear agronomic and environmental benefits in salt-affected soils, its adoption by farmers is often constrained by economic considerations. The initial investment cost of biochar production or purchase can be relatively high, particularly when derived from specialized pyrolysis systems or when transportation to farms is required [57]. These upfront costs pose a barrier for smallholder farmers in salt-affected regions, where input affordability is a critical determinant of technology adoption. However, when considered over the medium to long term, biochar application offers substantial economic advantages. By improving soil structure, reducing salinity-induced stress, and enhancing nutrient and water retention, biochar contributes to higher crop yields and greater yield stability under stress conditions [58]. Furthermore, biochar can generate co-benefits beyond direct yield gains, including reduced fertilizer requirements through improved nutrient use efficiency, and potential income streams from carbon markets or environmental credit schemes where biochar is recognized as a carbon sequestration tool [59]. These additional benefits improve the cost-benefit balance for farmers, particularly when policy or market mechanisms support the valuation of ecosystem services.

3.4. Interaction of Biochar with Dynamic Soil Microbial Communities and Saline Environments

The interaction between biochar and soil microbial communities under saline conditions represents a critical yet underexplored dimension of its efficacy as a soil amendment. Biochar can serve as a microhabitat and energy source for soil microorganisms due to its porous structure, high surface area, and variable chemical composition. These properties facilitate microbial colonization and potentially enhance microbial diversity and activity, which are vital for nutrient cycling, organic matter decomposition, and overall soil health [60]. In saline soils, where microbial communities are often disrupted by osmotic stress and ion toxicity, biochar has been shown to partially ameliorate these conditions by adsorbing excess sodium ions and improving the soil's physical environment, thus creating a more hospitable niche for beneficial microbial populations [45]. However, the influence of biochar on microbial dynamics in saline soils is not universally beneficial and may vary depending on the biochar's properties (e.g., pH, electrical conductivity, and aromaticity), the native microbial community, and the degree of salinity. Some studies report shifts in microbial community composition toward halotolerant species, while others observe enhanced activity of plant growth-promoting rhizobacteria (PGPR), which can facilitate plant adaptation to salt stress through mechanisms such as nitrogen fixation, phytohormone production, and 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase activity. Halotolerant plant growth-promoting rhizobacteria (HT-PGPR) produce a variety of secondary metabolites such as osmoprotectants, exopolysaccharides, and volatile organic compounds. These substances play a crucial role in enhancing plant growth and alleviating the negative impacts of salinity stress. The potential of HT-PGPR as a biological approach to counteract the detrimental effects of excessive soil salinity is increasingly acknowledged, as they contribute to improved plant development, productivity, and the restoration of saline-degraded soils [61]. Furthermore, biochar-induced changes in microbial activity can influence the biogeochemical cycling of key nutrients such as nitrogen and phosphorus, potentially modifying their availability under saline conditions. Nevertheless, there is a paucity of long-term, field-based research evaluating how biochar influences the functional traits and stability of microbial communities over time in salt-affected soils. The potential for biochar to modulate microbe-mediated processes, such as nitrification, denitrification, and organic matter mineralization, under high-salinity regimes remains an important frontier. Future research must employ advanced molecular tools, such as metagenomics and transcriptomics, to unravel the mechanistic pathways through which biochar affects microbial functionality in saline environments. A systems-level understanding of these interactions is essential to optimize biochar formulations and application strategies for enhanced soil resilience and sustainable crop production in saline and climate-stressed agroecosystems. **Table 1** provides a general overview of the key physical-chemical properties of biochar and highlights their potential positive and negative effects on plant tolerance to various abiotic stresses.

Table 1. General summary of biochar physical-chemical properties and their positive and negative effects on plant abiotic stress tolerance.

Property	Effect	Positive effects on abiotic stress	Negative effects on abiotic stress
Surface area and porosity	High surface area and porosity improve water retention and nutrient holding capacity	Enhances doil water retention, improves drought tolerance	Excessive water retention can cause poor aeration, affecting root respiration

Continued

pH	Typically alkaline (pH 7 - 10), can modify soil pH	Neutralizes acidic soils, improving nutrient availability under stress	May increase soil pH too much, causing micronutrient deficiencies
Cation exchange capacity (CEC)	Increases CEC, enhancing nutrient retention	Improves nutrient availability under salinity and drought stress	May temporary immobilize some nutrients, reducing their availability
Organic carbon content	Stable carbon source improves soil organic matter	Enhances soil structure and moisture retention, improves tolerance to heat and drought	Slow decomposition can limit immediate nutrient release
Electrical conductivity (EC)	Indicates soluble salt content	Moderate EC can improve salt tolerance by regulating ion balance	High EC may increase soil salinity, harming plants
Nutrient content (N, P, K, micronutrients)	Biochar may contain or adsorb nutrients	Supplies or retains nutrients improving stress resilience	Nutrient imbalance if biochar is nutrient poor or adsorbs nutrients excessively
Hydrophobicity	Some biochars can be initially hydrophobic	Can reduce water loss from soil in drought conditions after conditioning	Initially reduces water infiltration, worsening drought stress
Heavy metal adsorption	Adsorbs heavy metals, reducing toxicity	Migrates metal toxicity under stress conditions	Can adsorb beneficial ions reducing their availability
Thermal stability	High stable carbon resists decomposition	Long-term improvement of soil properties helps stress tolerance	Persistence means slow nutrient release, limiting short-term effects

4. Future Perspective

The future role of biochar in mitigating soil salinity and enhancing plant growth under the pressures of climate change warrants critical evaluation within the broader context of sustainable land management and agroecological resilience. While numerous studies have demonstrated the capacity of biochar to improve soil physicochemical properties such as increasing cation exchange capacity, enhancing water retention, and reducing sodium ion toxicity, its effectiveness remains highly content-dependent, influenced by factors including feedstock type, pyrolysis conditions, application rates, soil type, and crop species. Under climate change scenarios, where salinization is intensified by sea level rise, erratic rainfall patterns, and increased evapotranspiration, the potential of biochar to buffer saline stress becomes increasingly relevant. However, the long-term stability and interaction of biochar with dynamic soil microbial communities and saline environments remain insufficiently understood.

Although biochar may improve plant performance through indirect mechanisms, such as modulation of rhizosphere microbial activity and enhanced nutrient use efficiency, these benefits are not universally observed across systems. Unregulated or excessive application to soils with normal fertility can impose chemical stress on crops, adversely affecting agricultural productivity. For example, high-dose biochar amendments in rice (*Oryza sativa L.*) systems have shown that while certain physical properties of biochar (e.g., from peanut hulls) can be beneficial, application at 5% (w/w) slightly increased grains per spike but significantly reduced spike number per pot and seed-setting percentage [62]. This high-dose treatment also caused declines in both the diversity and stability of soil bacterial and archaeal communities, accompanied by disruptions in microbial metabolic activity and nutrient cycling linked to alterations in the soil carbon-to-nitrogen ratio. These findings underscore the importance of dosage optimization and careful consideration of soil-microbe-plant interactions in biochar application.

Given these contradictory effects, there is a clear need for research to develop standardized protocols for biochar production and application, including optimized feedstock selection, pyrolysis conditions, particle size, and application rates. Standardization can help ensure more predictable and positive outcomes, minimizing potential adverse effects such as increased greenhouse gas emissions or microbial disruption, while maximizing the mitigation of salinity stress. A critical future direction involves moving beyond short-term, controlled-environment studies to robust, long-duration field trials that account for variable climate conditions. Furthermore, the integration of biochar with complementary practices, such as organic amendments, salt-tolerant cultivars, and precision irrigation, should be rigorously assessed to develop holistic strategies for managing salinity in climate-vulnerable regions.

Thus, while biochar holds significant promise for improving soil health and crop productivity under salinity stress, its application must be guided by a nuanced understanding of soil-plant-climate interactions, supported by interdisciplinary research, standardized protocols, and adaptive management frameworks.

5. Conclusion

Abiotic stresses such as drought and salinity are escalating threats to global agricultural productivity, driven by climate change and soil degradation. Biochar has emerged as a promising amendment to alleviate these stresses by improving soil structure, enhancing nutrient retention, and modulating microbial activity; however, its efficacy remains highly variable and context-dependent. While studies highlight biochar's potential to increase water retention, buffer ion toxicity, and influence microbial communities, the underlying mechanisms, particularly under field conditions and over long timescales, are still poorly understood. High-dose applications may disrupt microbial diversity and metabolic processes, posing risks to soil health and crop yield, especially in sensitive monoculture systems. Moreover, the predominance of short-term, greenhouse-based studies limits our understanding of biochar's performance in complex, climate-vulnerable agroecosystems. Future research should aim to elucidate how biochar feedstock, pyrolysis conditions, and application rates interact with soil types and microbial communities to shape long-term soil health and crop productivity under abiotic stress. It is also critical to clarify the mechanisms governing biochar's effects on microbial diversity, nutrient cycling, and greenhouse gas emissions in field conditions over multiple growing seasons. In addition, the development of integrated management strategies that combine biochar with organic amendments, precision irrigation, and salt-tolerant cultivars is needed to create context-specific, climate-resilient agroecosystems. Therefore, while biochar holds substantial promise as a climate-resilient soil amendment, it cannot be viewed as a universal solution. Its use must be guided by integrated, evidence-based land management strategies that consider the complex interactions among soil properties, microbial ecology, plant physiology, and climate variability. Only through such multidisciplinary, precautionary, and context-specific approaches, informed by long-term and mechanistic research, can biochar be effectively harnessed to mitigate abiotic stress and secure sustainable food systems.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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