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Different Approaches to Reduce Salinity in Salt-Affected Soils and Enhancing Salt Stress Tolerance in Plants

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Abstract

Salt stress is one of the most harmful environmental stresses in recent times and represents a significant threat to food security. Soil salinization is caused by spontaneous natural processes of mineral dissolution and human activities such as inappropriate irrigation practices. Natural geological progressions like weathering of rocks, arid climate, and higher evaporation, as well as anthropogenic activities, including the use of brackish water for irrigation, and poor tillage operations, are the foremost causes of soil salinization. Typical characteristics of saline soils are salt stress, high pH, and lack of organic carbon, as well as low availability of nutrients. Disruption of precipitation patterns as well as high average annual temperatures due to climate change additionally negatively affects the process of soil salinization. Productivity and ability to support crop growth are reduced on saline soil. Salinity-induced stress reduces plant growth by modulating the antioxidative system and nutrient orchestration. The aim of this work is to show that the mentioned problems can be alleviated in several ways such as the addition of biochar, exogenous application of several elicitors, seed priming, etc. Research has shown that the addition of biochar can significantly improve the recovery of saline soil. The addition of biochar has no significant effect on soil pH, while the cation exchange capacity of the soil increased by 17%, and the electrical conductivity of the saturated paste extract decreased by 13.2% (depends on the initial salinity and the type of biochar raw material). Moreover, biochar enriched with silicon increases the resistance of bananas to salt stress. In addition, exogenous application of several elicitors helps plants to alleviate stress by inducing stress-related physicochemical and molecular changes (selenium, sulfur, silicon, salicylic acid). Finally, seed priming showed positive effects on metabolomics, proteomics and growth of plants subjected to abiotic stress. Priming usually involves immersing the seed in a solution for a period of time to induce physiological and metabolic progression prior to germination.

Keywords

Salt-Affected Soils, Salt Stress, Biochar, Elicitors, Seed Priming

1. Introduction

Soil is a complex and dynamic matrix with a large variety of species that inhabit it. The basic metabolic fuel for ecosystem functioning and soil activity is soil organic matter (SOM). In addition to supporting a variety of ecosystem services like nutrient cycling, carbon (C) sequestration, climate regulation, and flood mitigation, soil is essential to life as we know it. Investigating the diversity and concentration of low molecular weight metabolites or the soil metabolome, as a subset of SOM, therefore has the potential to significantly advance our knowledge of the behavior, fate, interaction and functional importance of small organic molecules in soil. The metabolome, consisting of a wide range of chemical classes such as amino acids, peptides, lipids, and carbohydrates, is an indirect consequence of multiple levels within the biological hierarchy, particularly the metagenome, metatranscriptome, and metaproteome [1].

Salt-affected soils include saline and sodic soils. Saline soils contain an excessive amount of soluble salts which makes it difficult to absorb water from the soil. On the contrary, sodic soils carry high amounts of adsorbed sodium ions that damage soil structure. Soils become hard and compacted when dry and sticky when wet. Both saline and sodic conditions considerably reduce the agricultural productivity (**Figure 1**).

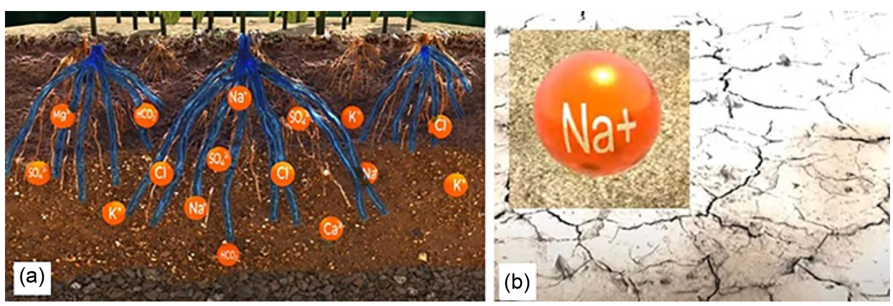

Figure 1. Salt-affected soils (a) saline and (b) sodium condition [2].

Saline and sodic soils are naturally present in arid, semi-arid and coastal environments. In these soils halophytic (in Latin, *halo* = salt + *phyte* = plant) vegetation is present.

Soil salinization is caused by spontaneous natural processes of mineral dissolution and human activities such as inappropriate irrigation practices (poor quality water), removal of deep rooted vegetation, water pumping at the coastal plains, and overuse of fertilizers [2] [3].

The geographic distribution of the natural source areas, the routes for more salt dissemination, and the locations of the areas that may be vulnerable to human-induced salinization are all determined by the salts' origin. The weathering of the fundamental minerals found in crystalline rocks is the source of all salts. From this beginning point, salts are reorganized at the earth's surface and become the building blocks of sedimentary rocks and loose sedimentary deposits. After the sedimentary and crystalline hard rocks weather, they escape from the salt-rich sediments or are released into the soil system [4].

About ~20% of the irrigated agricultural area, besides 6% of the global area, is salt-affected [5]. Natural geological progressions like weathering of rocks, arid climate, and higher evaporation, as well as anthropogenic activities, including the use of brackish water for irrigation, and poor tillage operations, are the foremost causes of soil salinization [6]. Salt is an inevitable pollutant that negatively affects soil health and fertility, reducing plant nutrient use efficiency. Typical characteristics of saline soils are salt stress, high pH, lack of organic carbon and low availability of nutrients [7]. Salinity stress also caused a considerable decrease in growth and yield because it decreased the osmotic potential, water uptake, and caused leaf rolling, chlorosis, and necrosis. It also disrupted the integrity of the membrane, DNA, and proteins, prevented the uptake of nutrients and water, and caused oxidative and ionic stress.

Declining water quantity and quality and poor land, water and crop management practices lead to increased soil salinity, land degradation, desertification and threaten the overall sustainability of crop production systems in irrigated drylands [8]. Disruption of precipitation patterns as well as high average annual temperatures due to climate change additionally negatively affects the process of soil salinization. Productivity and ability to support crop growth is reduced on saline soil [9].

Agriculture covers about 38% of the Earth's land surface, divided into 1.5 billion hectares of cropland and 3.4 billion hectares of pastures [10]. To meet projected food demand in 2050, an additional 0.2 to 1 billion ha of agricultural land may be required [11].

Crop production and food security in regions with low rainfall, i.e. on saline soils, and the use of low-quality groundwater for irrigation, is a major challenge [12].

According to FAO, more than 424 million hectares of topsoil (0 - 30 cm) and 833 million hectares of subsoil (30 - 100 cm) are salt-affected [13] and it is anticipated that 50% of the world's arable lands will be lost due to soil salinity by 2050 [14] [15].

If proper soil amelioration measures are not adopted, salinity may become a conspicuous environmental threat worldwide. Additionally, it has become very important to effectively utilize salt-affected marginal areas for agricultural purposes [16]. Salt toxicity augments the synthesis of reactive oxygen species (ROS) which injure plant cells [17]. Hence, salted plants exhibit leaf burns and necrotic lesions due to reduced photosynthesis and degradation of photosynthetic pigments [18]. Plant leaves deficient in chlorophyll content develop poor roots and shoots.

1.1. Coastal Lands

Coastal lands are key arable land reserves that play a vital role in ensuring future global food security. In arable coastal lands, low soil quality often results in limited crop yields and soil organic carbon (SOC), making them promising sites for increasing soil carbon sequestration and agricultural production. Li *et al.* [19] investigated the Yellow River Coastal Agricultural Region (YRD) in China. Their experiments were conducted for 11 years and tested the adaptability of the denitrification-degradation model in the coastal area of agricultural land, as well as spatio-temporal changes in regional SOC stocks and the possibility of increasing yield from 2020 to 2100. The results showed that the promotion of single cotton cultivation in coastal saline-alkaline soils would result in at least 88.2% of agricultural land being converted into carbon sinks. In contrast, the promotion of wheat-maize rotation system cultivation can promote regional SOC sequestration as a whole, with a maximum increase of 31.90 $Mg \cdot C \cdot ha^{-1}$. By 2100, SOC stocks were reduced on cotton and wheat-maize agricultural land by 3.9% and 11.6%, respectively. Except for agricultural areas with a wheat-maize crop rotation system, SOC stocks in all other scenarios are predicted to reach their theoretical maximum values before 2050. SOC stocks in cotton agricultural areas by 2100 have increased by 16.7% or 21, 6%, while SOC stocks in agricultural areas of wheat and corn increased by 1.8% and 4.8%, respectively. Based on their research results, they discovered a mutually beneficial relationship between yield increase and SOC sequestration on coastal agricultural lands under climate change, as well as the potential for future SOC sequestration. Through this project, they offered scientific support for land management and strategic decision-making on mitigating climate change in coastal saline-alkaline agricultural lands.

1.2. Marginal Lands

One of the main elements of the land evaluation systems is the assessment of soil quality. Prior to 1970, the purpose of evaluating soil quality was to determine if the soil was suitable for agricultural growth or to estimate productivity. Estimating productivity levels remained the primary goal of using soil quality indicators between 1970 and 1990. Test kits for measuring soil quality, biochemistry analysis, and multivariate statistics were utilized between 1990 and 2010 to determine productivity, environmental deterioration, and indices of animal and human health. Starting in 2010, the primary goals involved utilizing high-throughput technologies to analyze resistance and resilience, as well as multi-functionality and ecosystem services. In terms of land fertility, land evaluation techniques might be qualitative, quantitative, or a combination of the two [20].

The definition of land quality, according to Rossiter's 1996 paper [21], is "the process of predicting the potential use of land based on its properties". Land quality is defined as "a complex property of land that acts in a way that differs from the action of other land qualities in its influence on the suitability of land for a specific type of use; the ability of land to meet specific land use requirements."

There are 2.7 billion hectares of marginal land (marginally appropriate, extremely marginally suited) in the world, of which 1.5 billion hectares are uncultivated land that may be utilized for agriculture but isn't currently. However, with more effective utilization, many places classified as marginal could move out of this category.

Biophysical soil characteristics may not be the only factor for defining marginal land. In the early 1800s, the concept of marginal land has been introduced as the Theory of Rent [22]. The 19th century saw the beginning of extensive scientific research into the low productivity of lands. In 1932, Peterson and Galbraith [23] initiated the detailed development of a novel theory about marginal land types, within the framework of a contemporary land use planning concept. From the beginning of the marginal land theories, terms such as „physical marginal land," "production marginal land," and "economic marginal land" have been employed interchangeably and with varying purposes.

The need for more thoughtful and sustainable land use planning has increased in recent decades due to the expanding population and the extreme weather brought on by climate change. As a result, the ideas of prime land and marginal land need to be revisited from time to time [24]. Because different regions, nations, and organizations have diverse goals, their definitions of marginal land and its application domains vary. Soil scientists frequently use the physical and production marginality of lands. A soil's physical attributes, salinity, sodicity, water management, and other yield-affecting factors are increasingly being used as main markers of marginality. In addition to having low production, some of the impacted sites have restrictions that make it impossible to use them for conventional agricultural activities.

Criteria affecting yield, such as soil conditions including sodicity, salinity, water management and physical characteristics are becoming primary indicators of marginality [25]. Areas that have low productivity and cannot be used for traditional agriculture can be classified as Less Favored Areas, which can be translated as marginal land [26] further to productivity.

It is important to remember that prime land can degrade into marginal land or unproductive land due to environmental factors, primarily human impact. However, marginal land, and sometimes unproductive land, can be converted back into productive land through targeted improvement or appropriate land management.

The management or kind of cultivation of the land is frequently the only factor used to classify lands as prime, marginal, or unproductive. An important method for classifying that is land evaluation. The 20th century saw the beginning of the development of land evaluation systems based on biophysical characteristics.

According to Dauber *et al.* 2012 [27], it is surplus land that can be used to produce bioenergy. They look into this issue from the perspectives of ecosystem services and socioeconomics. Knowing which bioenergy production methods work best for the different kinds of excess land is crucial. One must consider yields, costs, inputs, and potential environmental and socioeconomic repercussions.

According to Wiegmann *et al.* 2008 [28], marginal land is deteriorated land that isn't being farmed right now. The most crucial thing, according to their work, is to locate degraded areas and examine the viability of using bioenergy or protecting natural habitats.

According to Khanna *et al.*'s work from 2021 [29], the definition of marginal land for bioenergy is likely to include land that is devoid of significant habitat value (socially marginal land for food crops), biophysically poor land, and land that is currently idle or fallow (economically marginal land for food crops). It may also include land that is currently in crop production but is losing soil organic matter, experiencing erosion or high nutrient run-off, or forgoing significant habitat value.

On the one hand, land uses that are on the edge of economic viability have been characterized as marginal lands in Europe [30]. The term "margin of economic viability" is ambiguous because a site may be productive for one purpose or location but not for another due to the same attributes that render it „marginal" in another [31] [32]. However, due to soil suitability and other land use restrictions, soil scientists usually employ physical marginality and productivity marginality of lands. Areas classified as marginal lands have low productivity in addition to limitations that render them inappropriate for use in agriculture [33].

Since it is illegal in China to use prime land for the production of bioenergy, energy crops are grown on wasteland and paddy fields which are defined as marginal lands and include natural grasslands, sparse forests, scrublands, and underused land, instead of prime land [34].

The Asia-Pacific Economic Cooperation Energy Working group (APECEWG) [35] claims that the marginal lands are hard to farm, have a harsh climate, and have poor physical qualities. Inadequate precipitation, high temperatures, low soil quality, steep topography, and other agricultural limitations can also be characteristics of such regions.

2. The Role of Biochar to Salt Stress

More than 100 countries have saline soils, which are widely distributed through-out arid and semi-arid parts of the globe. Irrigation of salt-affected infertile soils is essential to addressing the concerns of global food security. Salt-affected land is restored with a variety of inorganic and organic additions. Geographical and physicochemical soil features unique to a given region play a major role in the selection of a sustainable ameliorant. As a soil amendment, biochar, a solid carbonaceous residue formed at temperatures between 300 and 1000˚C while lacking or containing oxygen, has garnered a lot of interest lately [36]. An increasing amount of research indicates that adding biochar can help salt-affected soils' chemical, biological, and physical characteristics [37].

Salt-affected soil has become one of the major threats to soil health. However, the evaluation of biochar amendment effects and the underlying mechanisms on the physical, chemical, and biological indicators used for assessing the health of salt-affected soils is lacking. This review summarized biochar performance and mechanisms in improving the health of salt-affected soils. Biochar addition significantly improved soil physico-chemical properties (**Figure 2**) by enhancing aggregate stability (15.0% - 34.9%), porosity (8.9%), and water retention capacity (7.8% - 18.2%), increasing cation exchange capacity (21.1%), soil organic carbon (63.1%), and nutrient availability (31.3% - 39.9%), as well as decreasing bulk density (6.0%) and alleviating salt stress (4.1% - 40.0%). Following biochar incorporation, soil biological health can also be improved, particularly enhancing microbial biomass (7.1% - 25.8%), facilitating enzyme activity (20.2% - 68.9%), and ultimately increasing plant growth.

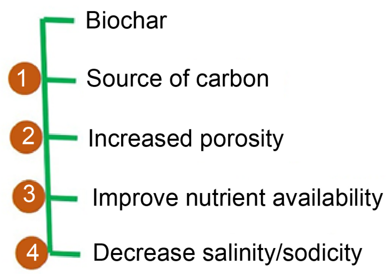

Figure 2. Improved soil physico-chemical properties by addition of biochar.

To properly assess the health of salt-affected soils, it is important to select indicators related to ecological service functions including plant production, water quality, climate change, and human health. This will improve the evaluation of soil multifunctionality and enhance current soil health assessment methods. Finally, limitations and future needs of biochar research and biochar-based technologies for soil health assessment in salt-affected soils are discussed. Based on a global meta-analysis to illustrate biochar effects on salt-affected soil health indicators, this review offers valuable insights for developing sustainable biochar-based tools for remediating salt-affected soil.

Salt-affected soil has become one of the main threats to soil health. However, there is a lack of assessment of the effects of biochar amendment and the underlying mechanisms on the physical, chemical and biological indicators used to assess the health of salt-affected soils. In their review paper, Yuan *et al.* [38] presented that the addition of biochar can significantly improve the physicochemical properties of soil affected by salt. Namely, they claim that the addition of bio-oil increases aggregate stability in the range of 15% to 35%, porosity of about 9% and water retention capacity between 8% and 18%, increasing cation exchange capacity by about 21%, organic carbon in the soil by about 63% and availability of nutrients by 31% - 40%, as well as a reduction in bulk density by 6% and relief from salt stress by 4% - 40%. The addition of biochar improves the biological health of the soil by increasing microbial biomass between 7% and 26%), facilitating enzyme activity by 20% to 69% and finally increasing plant growth.

Zhang *et al.* 2019 [39] tested the effect of biochar prepared from rice straw at a temperature of 300˚C and 600˚C on mitigating salt (NaCl) stress in rice soil and regulating the biochemical characteristics of Jinyuan 85 (a salt-tolerant rice variety) and Nipponbare (a rice variety sensitive to salt). Biochar prepared at 600˚C had higher adsorption properties, and bulk density, electrical conductivity, exchangeable Na^+ and exchangeable Cl^- in soil under salt stress were significantly reduced by its application. Biochemical characteristics of rice seedlings were significantly improved in response to biochar application and positively influenced salt accumulation in rice seedlings and root and leaf microstructure of rice seedlings under salt stress. The research showed that biochar prepared at 600˚C has a positive role in alleviating the inhibitory effects of salt stress on rice seedlings and can be useful as an additive to saline soil to improve the growth of rice plants.

Addition of Biochar

Salt stress is one of the most harmful environmental stresses in recent times and represents a significant threat to food security. There is scientific evidence that biochar enriched with silicon increases the resistance of bananas to salt stress. In addition, silicon in biochar has been shown to be effective in increasing chlorophyll, carotenoids, calcium (Ca^{2+}) and potassium (K^+) in banana leaves. Silicon-rich biochar alleviated salt stress by increasing the intake of Ca and K, and enhanced the activity of antioxidant enzymes [40].

Nasiri *et al.* 2024 [41], conducted a two-year assessment of the physiological and biochemical properties of beans with and without the presence of salicylic acid in a concentration of 0.5 mM and 1 mM. In addition, the research was carried out in the presence of biochar (2.5% per soil weight) and without the presence of biochar, and biochar modified with phosphoric acid and biochar modified with sulfuric acid, both with by 1.25% per soil weight. Physical and chemical properties of the initial soil and the biochar used in the experiment are shown in **Table 1**. NaCl was used to induce salt stress.

Table 1. Physical and chemical properties of the initial soil and the biochar used in the experiment [41].

Parameter	Initial soil	Biochar
N (%)	0.07	0.5
P ($mg \cdot kg^{-1}$)	10.8	0.11
K ($mg \cdot kg^{-1}$)	18.8	0.10
pH	8.2	6.9
EC ($cm \cdot S \cdot cm^{-1}$)	0.8	1.02
CEC meq/100g soil)	10.5	-

The results showed that bean plants are significantly affected by salt stress, which affects their biochemical characteristics (increased the PC, CAT, POX, PPO, and MDA). However, the addition of biochar to the soil and the use of salicylic acid, individually or in combination, were found to improve plant growth, enzyme activity and grain yield under high salinity conditions (**Table 2**). From the results, it was revealed that excessive use of biochar and salicylic acid may be useless because biochar increases soil porosity causing a negative effect on water availability. Additionally, excessive use of salicylic acid results in a negative impact on the biochemical and enzymatic properties of the plant [42] [43] under salinity conditions. Although the study on the effects of biochar and salicylic acid on beans under salinity stress appears to provide valuable insights, it has some limitations that need to be considered. Thus, this approach could be particularly effective in managing salinity problems in arid and semi-arid regions, highlighting the potential of biochar and salicylic acid to improve plant resistance in such conditions.

Wang *et al.* 2024 [44] carried out a meta-analysis from 99 peer-reviewed articles and concluded that the addition of biochar can significantly improve the recovery of saline soil. The research results also showed that the addition of biochar has no significant effect on soil pH, while the cation exchange capacity of the soil increased by 17%, and the electrical conductivity of the saturated paste extract decreased by 13.2% (depends on the initial salinity and the type of biochar raw material). They emphasized that additional research is needed in terms of the characterization of biochar and the impact of biochar on salt resistance and plants that do not tolerate salt in soils.

Oil obtained from beet seeds (*Brassica rapa L.*) is a good source of biofuel and nutritious cooking oil. In addition, the root of this beet is used in the treatment of various types of cancer and other diseases, but also as animal feed. Cultivation of high-yielding cultivars resistant to salinity, easy access to the use of areas affected by salt [45] [46].

Azadi and Raiesi, 2021 [47] experimentally demonstrated that the addition of 1% sugarcane biochar (SCB) to cadmium-contaminated soil under saline conditions could improve soil microbial and biochemical functions by up to

Table 2. Variance analysis of the effect of soil salinity (SS), biochar (BiO) and salycylic acid (SA) on PC (proline content), CAT (catalase), POX (peroxidase), PPO (polyphenol oxidase), H_2O_2 (hydrogen peroxide), MDA (Malonidialdehyde), and the grain yield of bean plants [41].

S.O.V.	df	PC	CAT	POX	PPO	H_2O_2	MDA	Grain Yield
Year	1	0/0291 ns	0.0004 ns	0/00002 ns	62/91 ns	0/0192 ns	43/42 ns	701.3 *
Block	6	0/1304 ns	0/0066 ns	0/00032 ns	13/18 ns	0/0121 ns	10/48 ns	82.79 ns
SS	2	0/1081*	0/0066*	0/00282 ns	286/8*	0/4740 ns	102/5 ns	155.3 *
Bio	3	0/2219*	0/0073*	0/00,311*	1697/1*	0/1590 ns	77/53 ns	711.9 **
SA	2	0/8098 ns	0/0198 ns	0/00594 ns	1781/8 ns	2/3819 ns	616/4 ns	222.9 **
SS x Bio	6	0/3107**	0/0089**	0/00,426**	566/9**	0/7811**	390/1 ns	195.6 *
SS x SA	4	0/0452*	0.0004 ns	0/00,058*	461/3*	0/6778**	104/9 ns	4.896 *
Bio x SA	6	0/1084**	0/0021**	0/00,089**	485/6**	0/3690**	57/92 ns	43.93 *
SS x Bio x SA	12	0/0219**	0/0042**	0/00,006	306/4**	0/5449**	157/7 ns	25.86 **
Year x SS	2	0/0036 ns	0/0002 ns	0/00017 ns	11/68 ns	0/1083 ns	68/26 ns	6.39 ns
Year x Bio	3	0/0107 ns	0/0003 ns	0/00021 ns	68/98 ns	0/0537 ns	80/69 ns	23.21 *
Year x SA	2	0/0933**	0/0025*	0/00043 ns	205/6 n	0/2780 ns	41/57 ns	0.02 ns
Year x SS x Bio	6	0/0053 ns	0/0002 ns	0/00,023*	12/79 ns	0/0437 ns	97/31 ns	4.249 *
Year x SS x SA	4	0/0033 ns	0/0001 ns	0/00006 ns	54/86 ns	0/0106 ns	74/52 ns	0.326 ns
Year x Bio x SA	6	0/0063 ns	0/0002 ns	0/00008 ns	32/87 ns	0/0076 ns	97/65 ns	1.107 ns
Year x SS x Bio x SA	12	0/0023 ns	0/0004 ns	0/00,048**	23/08**	0/0248**	78/97**	0.967 ns
C.V (%)	-	8/95	30/9	17/2	3/97	7/04	3/2	7.291

* and ** significant at 0.05 and 0.01 levels, respectively; ns—non-significant.

280%. Two samples of biochar were prepared, one at 400˚C and the other at 600˚C, whereby the content of organic carbon in the soil increased by 89-127% and the content of dissolved organic carbon by 21% - 70%. This study showed that the application of biochar (1% w/w) prepared at 400˚C can be used in saline soils contaminated with cadmium to protect soil microbial communities from Cd toxicity, and to alleviate potential stresses associated with the simultaneous occurrence of Cd contamination and salinity on critical microbial and biochemical soil functions.

3. Seed Priming

Seed priming involves immersing the seed in a solution for a certain period of time to stimulate physiological and metabolic progression before germination. This technique is simple and can alleviate environmental stress on crops [48]. As priming agents can be used solution of growth regulators, osmoregulators, acids, nutrients, and minerals in pure water [49]. By applying exogenous elicitors, physical-chemical and molecular changes occur in plants and in this way relieve stress [50]. An increased percentage of seed germination, better photosynthesis, improved antioxidant system and enhanced vegetative growth in subsequently developed plants under various abiotic stresses were shown by seeds treated with the inorganic plant elicitor selenium, Se [51]. Other research group also faund that Se enhances plant stress tolerance, increases photosynthesis of photosynthetic pigments, activates antioxidant machinery, and promotes plant nutrition and stress tolerance [52]. Also, plant growth increased by application of the foliar spray of selenium under salinity regimes [53]. The primary treatment of *Brassica rapa* seeds grown on soil sprinkled with selenium salt had a beneficial effect on the reduction of salinity stress through the reduction of malondialdehyde (MDA), proline, electrolyte leakage, and hydrogen peroxide (H_2O_2) levels, following physiological parameters such as chlorophyll synthesis, sugar content, gas exchange, etc. [54]. Antioxidant enzymes increased the ability to scavenge reactive oxygen species (ROS) resulting in a higher K^+/Na^+ ratio. An in silico study showed a significant difference in the surface overlap of stress-responsive proteins (DREB, SOS3 and STXBP1) of *B. rapa*, which indicates the involvement of Se in the foliation interaction of NaCl with the enzyme.

4. Addition of Elemental Sulfur

Replenishment of salt-affected soils with elemental sulfur (S^0) is recognized for its potential to effectively reduce salinity and soil pH, thereby improving soil physico-chemical properties, promoting crop growth and yield improvement. Despite these known advantages, the widespread application of S^0 for the management of saline soils, especially in arid calcareous regions, remains limited. Al-Mayahi *et al*. 2024 [55] investigated the influence of S^0 on salt leaching, soil pH, nutrient uptake, plant growth, microbial diversity and community structure under alkaline-saline soil conditions. They carried out three different experiments: preliminary in a column without plants, a field with rhododendron grass (*Chloris gayana*) and a greenhouse with wheat (*Triticum spp.*). The research results showed that the incorporation of S^0 into the soil had a positive impact, resulting in increased salt removal, reduced soil pH and improved plant growth. In particular, soil amendment with 750 $kg \cdot S^0 \cdot ha^{-1}$ led to significant salt removal, more than double in the column experiment, approximately 91.3% in the field experiment and about 34.1% in the greenhouse experiment compared to the control. Addition of S^0 also significantly lowered soil and leachate pH in field and greenhouse experiments, with reductions of 3.3% and 6.3%, and 8.1% and 4.4%, respectively, compared to the control. The uptake of calcium and phosphorus by Rhodes grass was significantly increased by 75% and 14%, respectively, compared to the control. The organic matter content in the soil increased significantly from 0.6% to 1.5% compared to the control. This overall improvement in soil conditions resulted in significant increases in Rhodes grass and wheat yields of 13% and 59%, respectively. Finally, their results suggest that soil amendment with S^0 is a promising strategy for the sustainable management of calcareous salt-affected soils in arid regions.

Fertile soil salinity is a significant problem because it lowers agricultural production. This happens due to insufficient amounts of precipitation, salt is removed from the roots of the plants. Apart from the fact that salinization is accelerated by the lack of rain and the insufficient irrigation process, there are also limited intrinsic soil drainage properties. The most important anions (sulfates and chlorides) and cations (calcium, sodium, and magnesium) are designated as the main actors of soil salinity. Soil salinity affects the growth and development of the plant and is manifested by a smaller leaf area, chlorophyll content, stomatal conductivity, ion balance and generation of reactive oxygen species. Diffusion processes are limited in leaf mesophyll cells due to the reduced availability of CO_2, which affects photosynthesis. On the other hand, the excess of sodium and chloride ions absorbed through the roots accumulates in the leaves and leads to senescence with various degrees of chlorosis or necrosis. Then, the intracellular accumulation of sodium ions alters the potassium-sodium ratio, causing an osmotic imbalance and the generation of free radicals that affect several enzymes and pigments involved in photosynthetic processes [56].

Choudhary *et al.* [57] investigated the influence of saline soil (soil salinity/sodicity) on the physicochemical and microbiological properties of the soil at the surface (0 - 15 cm) and below the surface (15 - 30 cm) of the soil. Five soil types based on pH, electrical conductivity and salt concentration maintained over the last 25 years - high saline, moderate saline, high sodium, moderate sodium and normal were evaluated in microplots to understand changes in soil biological properties in relation to concentration salts. The results revealed that the highest values of pH, electrical conductivity, cation exchange capacity, percentage of exchangeable sodium, sodium adsorption ratio, anion and cation concentration, bulk density, infiltration rate, penetration resistance were observed in high saline and high sodium soils on the surface and subsurface layer of the soil. In the surface and subsurface layers, organic carbon (0.67% and 0.52%) and available N (110 and 195 $kg \cdot ha^{-1}$) were found higher under normal soil than salt-affected soils (% OC: 0.20 - 0.34 and 0.17 - 0.38; available N: 75 - 80 or 47 - 77 $kg \cdot ha^{-1}$). The utilization of amino acids, amines, carboxylic acids, phenolic compounds and polymers was the highest for normal followed by moderately saline soils, and the lowest was recorded for soil with a high amount of sodium. The effect of salt loading was also reflected in the reduced activity of soil enzymes such as dehydrogenase, aryl sulfatase, invertase, for various types of saline soil. Thus, with the increase of salt load, the chemical and physical properties of the soil deteriorated and directly affected the microbial population, activity and their diversity in the soil. The research results showed that the physico-chemical properties of soil, functional diversity, population and community of microbes strictly depend on the nature of salts and their concentration, which can affect soil quality and crop yield.

The most preferred cereal, which feeds about 35% of the world's population, is bread wheat (*Triticum aestivum L.*), which consists of 55% carbohydrates and makes up 20% of the calories in the food intake. Wheat is moderately tolerant to sodic stress (percentage of exchangeable sodium, 35-50%) and it depends on the plant species, intensity of land degradation and management practices. Sodic soils with a high percentage of exchangeable sodium adversely affect crop productivity because they tend to develop low porosity with a dense structure and high soil strength resulting in limited root penetration, nutrient uptake, plant-water availability and metabolic activity [58]. The yield loss percentage of wheat grown on salt-infested soils in India is about 20% - 43% or 4.1 million tonnes representing an economic loss of about US$ 0.76 billion [59].

5. Conclusion

Numerous studies point to the application of biochar on saline soils as a promising method of overcoming problems related to saline soils. Observations have shown that the application of biochar as an organic supplement can improve plant growth and the physical, chemical and biological properties of soil affected by salt. In other words, the availability of nutrients in salt-affected soils can be increased. One should be very careful here, considering that the application of biochar depends greatly on the type of soil, the presence of nutrients in the soil, and the mechanisms and processes that take place both in the soil and in the plants. However, saline and sodic soils cannot be successfully restored without removing sodium from the soil profile. Therefore, an optimal ratio of biochar, sodium and calcium must be found for a positive effect on plant growth. It is believed that biochar with higher calcium content and lower sodium content would have positive effects on plant growth.

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Conflicts of Interest

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

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