soil systems

Review

Review of Crop Response to Soil Salinity Stress: Possible Approaches from Leaching to Nano-Management

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Abstract: Soil salinity is a serious problem facing many countries globally, especially those with semi-arid and arid climates. Soil salinity can have negative influences on soil microbial activity as well as many chemical and physical soil processes, all of which are crucial for soil health, fertility, and productivity. Soil salinity can negatively affect physiological, biochemical, and genetic attributes of cultivated plants as well. Plants have a wide variety of responses to salinity stress and are classified as sensitive (e.g., carrot and strawberry), moderately sensitive (grapevine), moderately tolerant (wheat) and tolerant (barley and date palm) to soil salinity depending on the salt content required to cause crop production problems. Salinity mitigation represents a critical global agricultural issue. This review highlights the properties and classification of salt-affected soils, plant damage from osmotic stress due to soil salinity, possible approaches for soil salinity mitigation (i.e., applied nutrients, microbial inoculations, organic amendments, physio-chemical approaches, biological approaches, and nano-management), and research gaps that are important for the future of food security. The strong relationship between soil salinity and different soil subdisciplines (mainly, soil biogeochemistry, soil microbiology, soil fertility and plant nutrition) are also discussed.

Keywords: salt stress; salt-affected soil; gypsum; biochar; compost; PGPR; mycorrhizae

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1. Introduction

Several global problems face modern society. Soil salinity is one of these important global issues as it negatively affects crop production. The main causes of salt accumulation in soil include primary salinization from the weathering of rocks and seawater intrusion/spray in coastal areas and secondary salinization such as the over-use of fertilizers, irrigation with low quality water, waterlogging, and dumping or spilling industrial brine [1]. Soil salinity is viewed as soil degradation because soil degradation is viewed as something affecting not only plant growth, but also soil microbial attributes, soil functionality (e.g., biochemical cycling), and other soil ecosystem services [2]. Globally, more than 50% of irrigated croplands are experiencing soil salinization issues, which decreases plant growth, development, and survival [3]. Thus, soil salinity threatens global food security, and this issue is compounded given our changing climate [4]. Crop stress damage under soil salinity results primarily from ionic, osmotic, and oxidative stress. Plants need to be able to mitigate these stresses through the ionic, osmotic, and reactive oxygen species (ROS) homeostasis to be tolerant of salts in soil [5,6].

The chemistry of the salts found in soil, including their dynamics and physicochemical and biogeochemical properties, is very important [7]. Soil rhizosphere microbial communities, composition and enzyme activities can be changed as a result of soil ionic and osmotic effects [8]. Soil salinity can influence the availability of soil nutrients, microbial activity, and the relationships between soil organisms and soil fertility [9] as well as plant nutrition under such conditions [10]. Thus, there is an urgent need to improve crop productivity in saline soils through the use of management approaches [11]. Soil salinity management may include applying mineral nutrients and beneficial elements such as potassium [12], selenium [13], titanium [14], or silicon [15]. Soil organisms can be used to mitigate salinity by solubilizing nutrients via microbes [16,17] and mycorrhizal activities [10]. Bio-organic fertilizers [18,19] or organic biostimulants such as proline [15], biochar [20], compost [21], humic substances [22], and ascorbic acid [23] can improve crop performance in saline soils. Nano-management can also help, including using nano-Se [24,25], nano-Si [26], nano-ZnO [27], nano-CuO [28], nano-gypsum [29], and nano-carbon dots [30]. Soil salinity has a strong relationship with a variety of global issues, mainly climate change, food security, and the United Nations Sustainable Development Goals (SDGs). Thus, soil salinity should be mitigated using innovative strategies that support the SDGs. Soil salinization management is crucial for achieving several SDGs, such as SDG2 “Zero Hunger”, SDG3 “Good Health and Well-Being”, and SDG15 “Life on Land” [1,31–33].

Crop response to soil salinity stress is one of the most important topics in agricultural and environmental sciences. This response mainly depends on plant species and salinity stress levels, as well as the environmental conditions [34]. The response of plants to salinity stress can produce a variety of physiological and metabolic changes in the stressed plants during all growing stages starting from germination, the photosynthesis process, and other biosynthetic processes [5,35,36]. The level of crop response to soil salinity differs, ranging from sensitive, moderately sensitive, moderately tolerant, and tolerant depending on the properties and characteristics of the individual crops [37]. There are many suggested mechanisms to adapt cultivated crops to different salty soil environments [34]. These proposed mechanisms include mediating plant hormone signaling [36,38], regulating ion homeostasis [39], activating the osmotic stress pathway [40], and regulating cell wall organization [41]. Understanding these mechanisms, including different physiological, biochemical, and molecular responses to salinity stress, are considered crucial strategies to improve agricultural crop productivity [42,43].

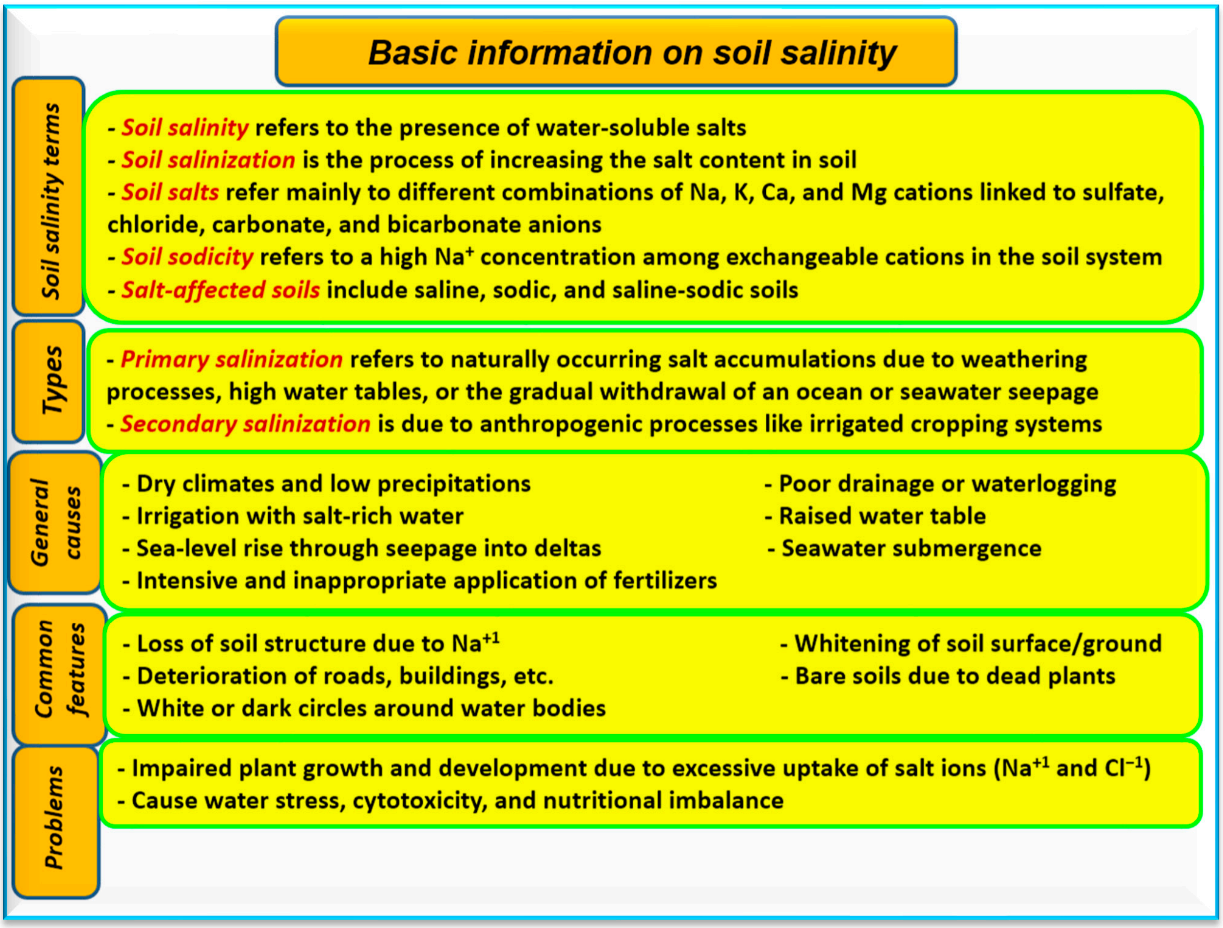
The current study investigated the story of soil salinity stress, the response of crops under such stress, the main drivers of these stresses, the expected consequences, and possible management approaches. Perspectives from both soil science and crop response to soil salinity will be discussed. Soil salinity management and mitigation approaches (mainly, the application of nutrients, organic amendments, microbial mitigation, and nano-management) are important issues in this review and will be highlighted.

2. Methodology of the Review

The current study was conducted due to the importance of the topic “soil salinity and crop response”. Literature searches were conducted using a selection of keywords: “soil salinity”, “salt stress”, “crop and salinity”, “soil salinity causes”, “salt-affected soils”, “salinity and soil biogeochemistry”, “salinity and soil microbes”, “salinity and nutrients”, “salinity and soil fertility”, “soil salinity and GIS”, “salinity mapping”, “soil salinity management”, “microbial mitigation of soil salinity”, and “nano-management of salinity”. The selection of the source literature depended on the significance of each source or journal, where the reputation and impact factor along with name of the authors and their experience in the studied field were important criteria. The most important databases searched were ScienceDirect, Springer, PubMed, MDPI, and Frontiers. The publication year (up-to-date publications from the last seven years were prioritized) and discipline-specific journals (related to soil and plant sciences) were important factors. The current project was designed to investigate the following questions: (1) What are the main causes, problems, and consequences of soil salinity? (2) What are the direct and indirect links between soil salinity and different soil subdisciplines? (3) What are the distinguishing features of salt-affected soils? (4) What is role of GIS and remote sensing in the evaluation and mitigation of soil salinity? (5) What are the main approaches for salt-affected soil management? (6) To what extent are nutrients, organic amendments, and microbial approaches effective tools for the mitigation of salt-affected soils? (7) Is nano-management of salt-affected soils a sustainable strategy? And (8) what are the suggested mechanisms of crop response to soil salinity? This review is unique because we are not aware of any other reviews focused specifically on the questions addressed as relates to nano-management of crops in salt-affected soils.

3. Soil Salinity and Global Issues

The accumulation of soluble salts in soil is referred to as salinization, whereas soil salinity is expressed as the concentration of soluble salts in soil solutions or extracts by measuring the *electrical conductivity* (EC) in dS m^{-1} at 25 °C [44]. This is one of the most important global issues affecting food security, agricultural production, and environmental sustainability [7]. Basic information regarding soil salinity is shown in Figure 1. Changing climates can drive soil salinization through processes such as rising sea levels [45], changing rainfall patterns [46], increasing air temperature leading to enhanced evaporation [47], and increased drought events [48]. Recent studies published on global issues related to soil salinity include a focus on topics such as reducing soil salinization by applying organic materials that increase net carbon sequestration [49], using drip irrigation [11], and soil-based technologies [50] for crop production [51].



Basic information on soil salinity

Soil salinity terms

- ***Soil salinity*** **refers to the presence of water-soluble salts**
- ***Soil salinization*** **is the process of increasing the salt content in soil**
- ***Soil salts*** **refer mainly to different combinations of Na, K, Ca, and Mg cations linked to sulfate, chloride, carbonate, and bicarbonate anions**
- ***Soil sodicity*** **refers to a high Na^+ concentration among exchangeable cations in the soil system**
- ***Salt-affected soils*** **include saline, sodic, and saline-sodic soils**

Types

- ***Primary salinization*** **refers to naturally occurring salt accumulations due to weathering processes, high water tables, or the gradual withdrawal of an ocean or seawater seepage**
- ***Secondary salinization*** **is due to anthropogenic processes like irrigated cropping systems**

General causes

- **Dry climates and low precipitations**
- **Irrigation with salt-rich water**
- **Sea-level rise through seepage into deltas**
- **Intensive and inappropriate application of fertilizers**
- **Poor drainage or waterlogging**
- **Raised water table**
- **Seawater submergence**

Common features

- **Loss of soil structure due to Na^{+1}**
- **Deterioration of roads, buildings, etc.**
- **White or dark circles around water bodies**
- **Whitening of soil surface/ground**
- **Bare soils due to dead plants**

Problems

- **Impaired plant growth and development due to excessive uptake of salt ions (Na^{+1} and Cl^{-1})**
- **Cause water stress, cytotoxicity, and nutritional imbalance**

Figure 1. A summary of important information on soil salinity including definition terms, different causes of salinity in soil, main features, and general problems. Sources: [2,8].

Soil salinity is strongly linked to issues including climate change, soil fertility, carbon sequestration, food security, and the SDGs. Extended drought periods and rapidly melting glaciers causing changes in water dynamics have led to a significant decline in agro-productivity, especially in semi-arid regions [51]. This impact can reduce crop biomass, soil organic carbon (SOC), microbial biomass carbon (MBC), and the flux of CO_2 and CH_4 under soil salinization [49]. The main drivers of soil salinity under climate change are presented in Figure 2. These drivers of salinization may include the low quality of irrigation water [52], poor soil drainage [53], increased surface air temperatures [54], the intrusion of salt water into coastal areas due to global sea level rise [55], and decreased precipitation rates [48]. Soil salinity may degrade both soils and vegetation [48], hindering global food security [4].

Salt-affected soils are most frequently associated with arid and semi-arid climates, where the amount of annual precipitation is not sufficient to leach the ions that create salt-affected soils out of the soil profile. The type of salts that accumulate and where they are found in the soil profile are determined by the amount of annual average precipitation, the presence of a source of the salts through either soil parent materials or some external source (e.g., groundwater, dust deposition, irrigation), and the physical properties of the soil that regulate water infiltration [56]. However, salt-affected soils can also form in humid environments given the right set of conditions. For example, sodic soils are found across southern Illinois in the USA, an area that sees approximately 1220 mm of precipitation per year. In the case of these soils, it has been proposed that microtopography established by permafrost during the Wisconsinan glaciation established water distribution relationships in the soils that allowed for the accumulation of sodium found in the parent materials [57].

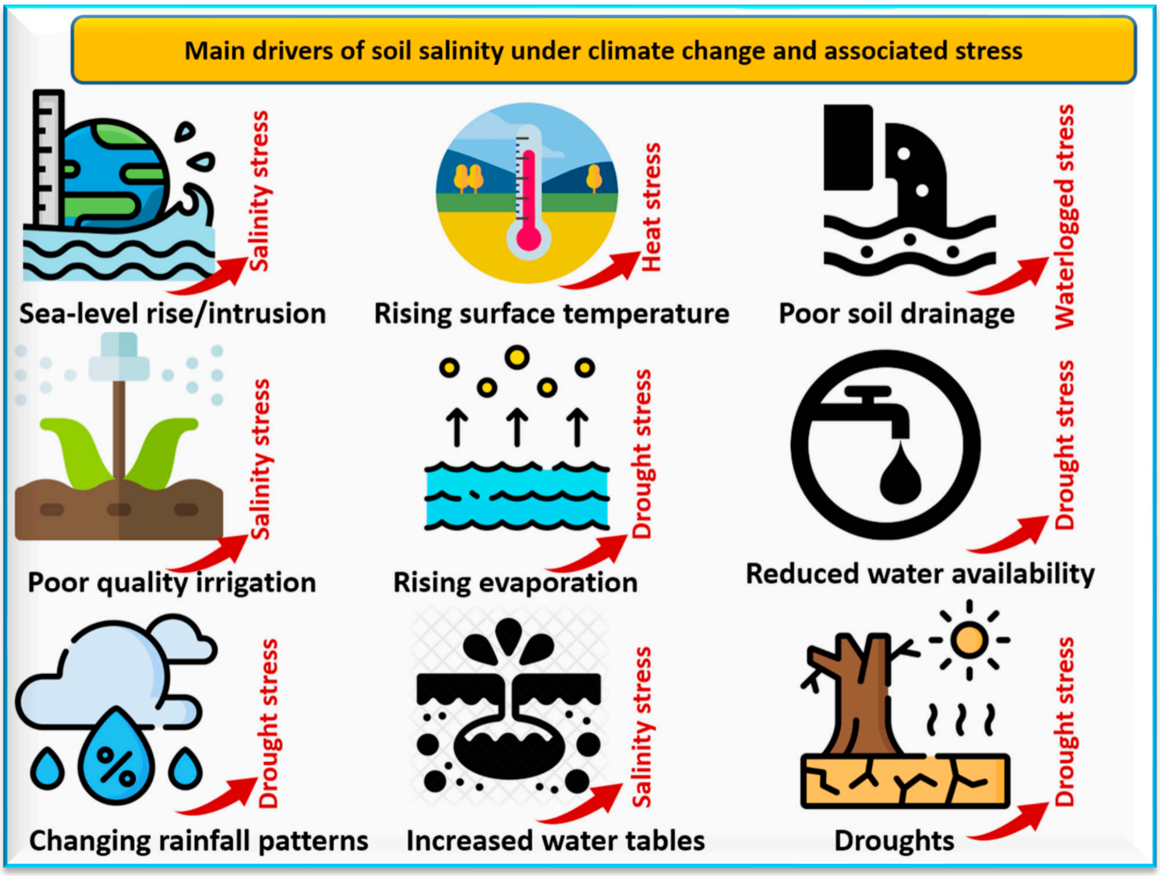


Figure 2. The main drivers of soil salinity under climate change include sea level rise, poor soil drainage, increasing evaporation, poor quality of irrigation water, reduced availability of water, increasing temperatures, droughts, and changing rainfall patterns. Adapted from Eswar et al. [48]. Images from https://www.flaticon.com/free-icon/, accessed on 22 September 2023.

4. Salt-Affected Soil Classification

Salt-affected soils are often classified according to the system developed by Richards [58]. This system is based on a combination of soil pH, the electrical conductivity of the soil saturation extract (ECe), and the exchangeable sodium percentage (ESP). Using these indicators, *saline soil* has a pH < 8.5, ECe > 4 dS m^{-1}, and ESP < 15. *Saline–sodic soils* have an ECe > 4 dS m^{-1} and ESP > 15. And, *sodic soils* have an ECe < 4 dS m^{-1}, ESP > 15, and a pH that is typically between 8.5 and 10. It is important to understand the type of salt-affected soil, because it makes a difference in soil management, mitigation, and reclamation. While the Richards classification is the most commonly used classification for salt-affected soils, it is important to note that other classifications exist. These include the FAO-UNESCO solonchaks and solonetz, which are broadly similar to saline and sodic soils, and the Russian system [59]. Solonchak (saline) soils have high salinity (ECe > 15 dS m^{-1}) within 125 cm of the soil surface and are divided into four units (gleyic, orthic, mollic, and takyric), whereas solonetz (sodic) are sodium-rich soils (ESP > 15) that may include gleyic, orthic, or mollic subdivisions. US Soil Taxonomy [60], the Canadian soil classification system [61], and the Australian classification system [62] also include ways of noting salt accumulation in the classified soils.

It is also important to note that several variables determine how a crop will respond to salt-affected soils, including the species and variety of the crop and a number of soil factors [59]. For example, sugar beet and durum wheat are fairly salt tolerant, with little reduction in yield as ECe increases from 0 to 7 dS m^{-1}. However, maize, soybean, tomato, and broad bean are much more sensitive to soil salinity, with maize undergoing a rapid decline in yields once ECe reaches about 2 dS m^{-1}, soybean about 2.5 dS m^{-1}, tomato about 3 dS m^{-1}, and broad bean about 3.5 dS m^{-1} [63]. Therefore, while 4 dS m^{-1} is a commonly used indicator of saline soils, it is not a particularly useful value when estimating the performance of a given crop. Another classification of saline soils is based on electrical conductivity and the expected impact on crop growth given that conductivity (Table 1).

Table 1. Soil salinity classes based on expected influence on crop yield. Table based on Stavi et al. [2].

Soil Salinity Class	Electrical Conductivity (dS m^{-1})	Crop Response	Example Crop Tolerance Level (dS m^{-1}) *
Non-Saline	0–2	No yield loss	Maize (1.7)
Slightly Saline	2–4	Yield is reduced in sensitive crops	Peanut (3.2)
Moderately Saline	4–8	Most crops experience reduced yields	Sorghum (6.8)
Strongly Saline	8–16	Only tolerant crops produce viable yields	Rye (11.4)
Very Strongly Saline	>16	Only halophytes perform well	Halophytes

* Crop tolerance level to soil salinity (ECe, the threshold value) according to FAO [37].

5. Soil Salinity from the Perspective of Different Soil Subdisciplines

All soil subdisciplines can be linked to soil salinity from different points of view. Low levels of salinity (0–2 dS m^{-1}) are not harmful to many cultivated crops, but higher levels (>4 dS m^{-1}) can cause considerable yield loss depending on crop tolerance, and several types of physiological, nutritional, and molecular damage can be realized [1]. In this section, three of the soil subdisciplines will be explored in detail to understand their links to soil salinity. Other soil science subdisciplines are briefly addressed in Figure 3.

Soil microbes have a promising role in the mitigation of soil salinity through the alleviation of and reduction in oxidative stress by endophytic and rhizospheric microbes [64] and in acting as significant selective agents on their host plants [65] in an eco-friendly approach [42]. The nutrient uptake by plants under salinity stress is controlled by the salinity level, ions present, plant species, and soil amendments. This depends on soil properties including soil pH and other biological, physical and chemical properties which control the bioavailability of nutrients to be taken up by the plants [66,67]. This may reflect many approaches related to soil fertility and plant nutrition in the mitigation of soil salinity through integrated nutrient management [68]. The interplay between different soil science branches and soil salinity can be noted in the biogeochemical perspective of microbial diversity and functions in saline soils [69]. Planting salt-tolerant crops is an effective approach, but producing new tolerant cultivars is needed [70].

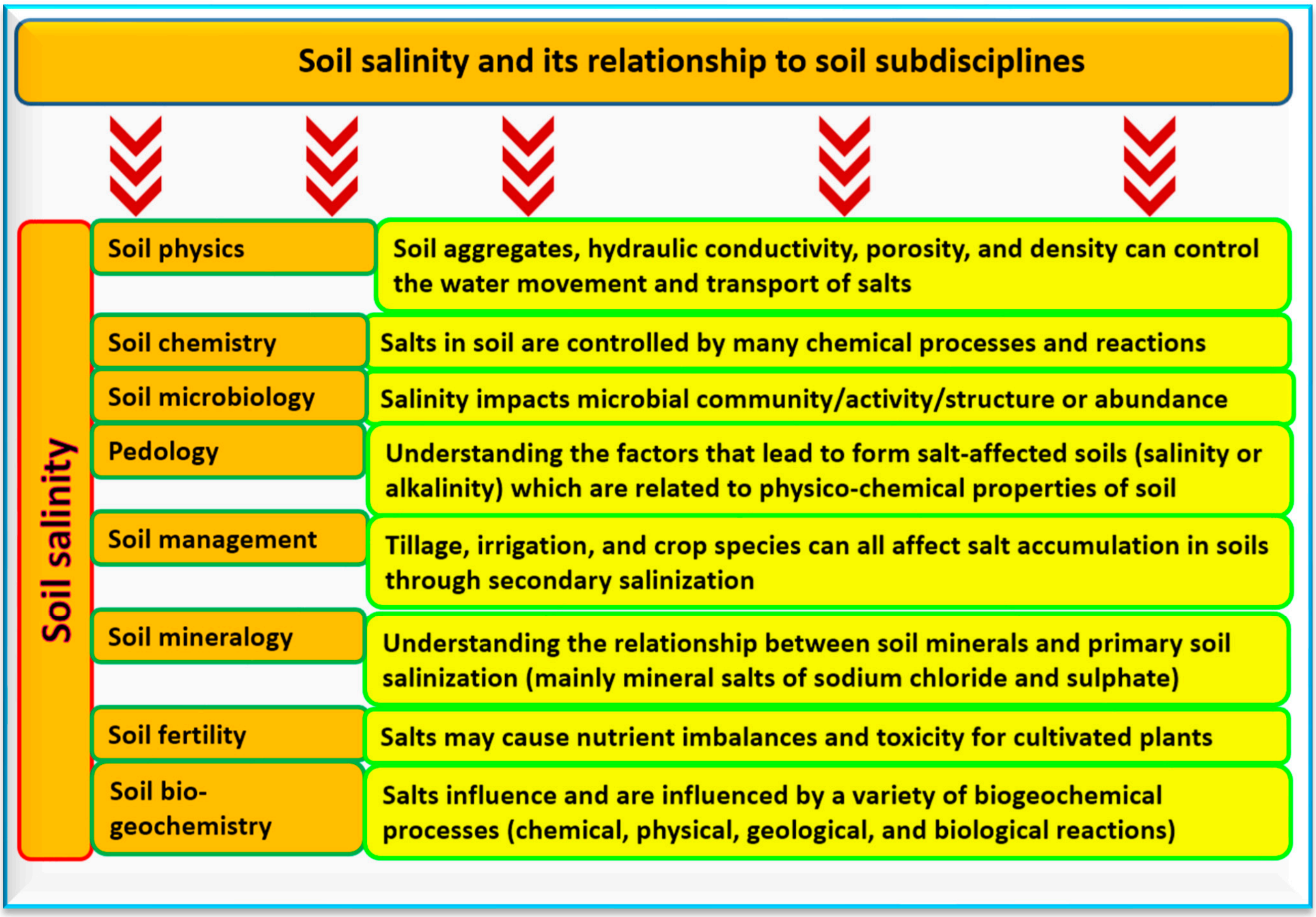


Figure 3. Relationships between soil salinity and soil subdisciplines. Sources: [1,7,8,42,52,64–94].

5.1. Soil Biogeochemistry

Soil biogeochemistry is the science that studies the cycling of elements in the rhizosphere or the agroecosystem through chemical, physical, biological, and geological processes and the interactions between living and non-living components of soils [71]. This discipline studies the effects of soil salinity on agricultural productivity through biogeochemical influences on soil organic carbon, soil microorganisms, land desertification, greenhouse gas (GHG) emissions, and biodiversity [7]. Topics mainly focus on the impact of biological, chemical, and geological processes in soil on controlling the dynamics, distribution, and behavior of salts in the rhizosphere and groundwater [72], on one side, and on cultivated plants on the other [8]. These processes have a large impact on soil productivity, quality, and degradation [73]. It is important to manage soils in agroecosystems so that soil biogeochemical processes promote soil health or quality [74]. One common soil management practice that impacts the relationships between soil biogeochemistry and soil salinity is the application of organic amendments that increase the complexity of microbial networks (Figure 4) [75].

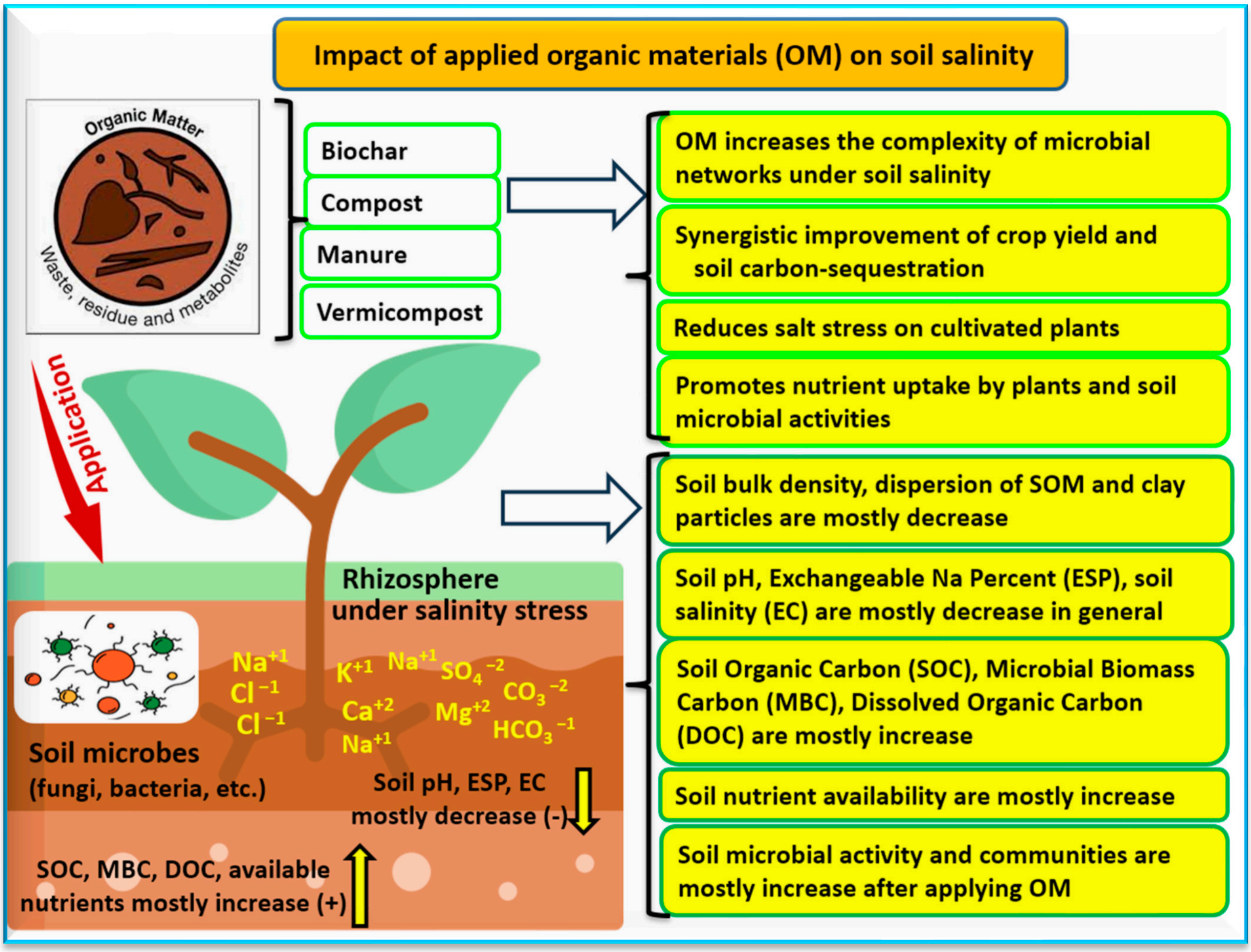


Figure 4. Applying organic materials to saline/alkaline soils can mitigate salinity/alkalinity stress by reducing ions in the soil solution (measured as electrical conductivity (EC) of the soil), bulk density, and exchangeable sodium percentage (ESP) and increasing nutrient uptake by plants, soil biological activity, soil organic carbon (SOC), microbial biomass carbon (MBC), and dissolved organic carbon (DOC). Adapted from [49,75].

Several studies have investigated the role of organic amendments in mitigating soil salinity and increasing microbial biomass (MBC), dissolved organic carbon (DOC), the bioavailability of nutrients (NPK and other nutrients), and the activity of many enzymes such as catalase, urease, phosphatase, invertase, and phenol-oxidase [76]. Studies into this relationship have involved applying compost [52], biochar [77], manure [76], vermicompost [78], and combinations of biochar and compost [20], biochar and vermicompost [79], and titanium, gypsum, and biochar composite [80]. Effective management of saline soils depends on reducing the soluble salt content and/or the ESP of the soil and the accumulation of sodium ions (Na^+) in cultivated plant tissues [81]. The influence of OM amendments on soil pH is variable and depends on the specific characteristics of both amendments and soils. For instance, biochar can have alkaline pH values that may increase soil pH [95,96]. The expectation is that OM amendments will usually lead to an increase in SMB, SOC, DOC and available nutrients, as presented in Figure 4 [96–99]. There is still a need for additional studies that investigate soil biogeochemistry and how it interacts with salt-affected soils.

5.2. Soil Microbiology

Soil microbes are very important to soil health or quality. Important functions carried out by microbes include the decomposition of organic matter, nutrient cycling, C-sequestration, and promoting soil fertility (Figure 5). Soil microbiology in saline soils mainly focuses on the relationship between soil salts and microbial structure, abundance, and activities. The mitigative role of microbes on cultivated plants under salinity stress is a very important issue [8,82,83]. The main soil microbial taxa that enhance the tolerance of cultivated plants under salinity stress include arbuscular mycorrhizal fungi (AMF), *Trichoderma* spp., *Pseudomonas* spp., *Bacillus* spp., *Enterobacter* spp., and *Serendipita indica* [8]. Plant–microbe interactions in salt-affected soils alter the rhizomicrobiomes in ways that promote plant growth [84]. This microbial role has been applied successfully under treated wastewater irrigation in saline soils during the cultivation of bioenergy crops [85]. Building microbial communities able to enhance plant growth under salinity stress through the use of OM is a crucial objective or strategy [86]. There is still a need for considerable research into the role and function of soil microorganisms in salt-affected soils.

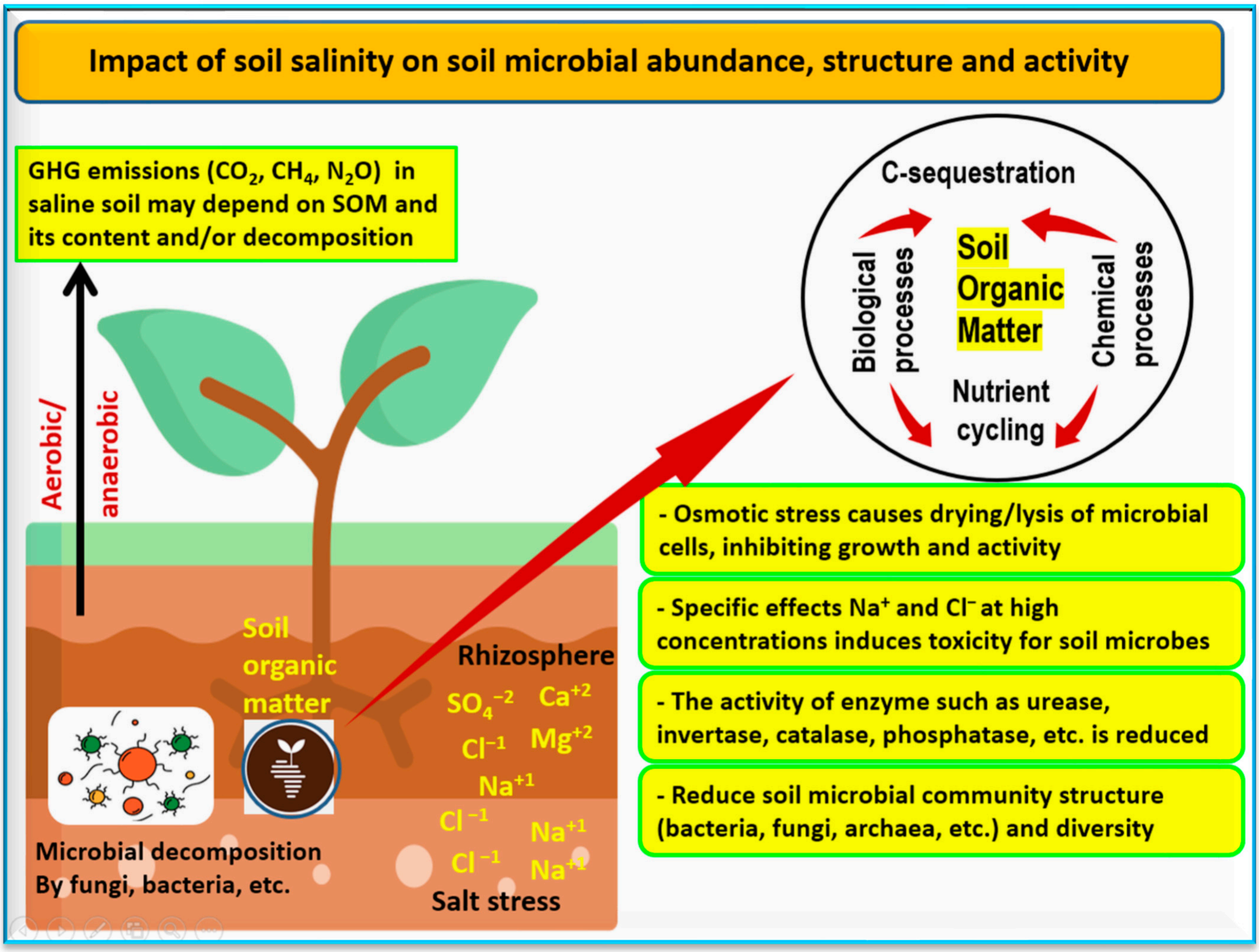


Figure 5. Soil salinity has a negative impact on soil microbial abundance, structure and activity through both osmotic stress and specific ion stress. Sources: [8,82–86].

5.3. Soil Fertility and Plant Nutrition

Although sodium, chloride, calcium, magnesium, and other ions have important roles in plant nutrition, the high content of Na^+ and/or Cl^- in salt-affected soils can cause stress in cultivated plants. Elevated levels of other nutrients (Ca, K, Mg, etc.) can also cause nutrient imbalances, negatively affecting crop yields [100]. Salinity can reduce enzyme activity [87], soil respiration [88], soil microbial biomass [89], and the bacterial growth rate [90], all of which influence biogeochemical cycling [91] which impacts soil fertility [9,92]. Soil salinity stress is aggravated in polluted environments, where cultivated plants suffer from soil nutrient and water uptake that are insufficient to meet their needs [90]. Extra stress on cultivated plants has been documented in saline soils polluted with heavy metals [93] and organic pollutants [94]. The combination of salinity and pollution can form high redox potential values, which control the release/uptake/desorption of pollutants (e.g., As, Cd, Cu, Pb, and Zn) [93]. Polluted saline soils also complicate remediation efforts, as treatments intended to alter microbial biomass/activity, release/degrade pollutants, and change nutrient or contaminant bioavailability may not function the same way as they do in non-polluted or non-saline soils [94].

6. GIS, Remote and Proximal Sensing, and Salinity Mapping

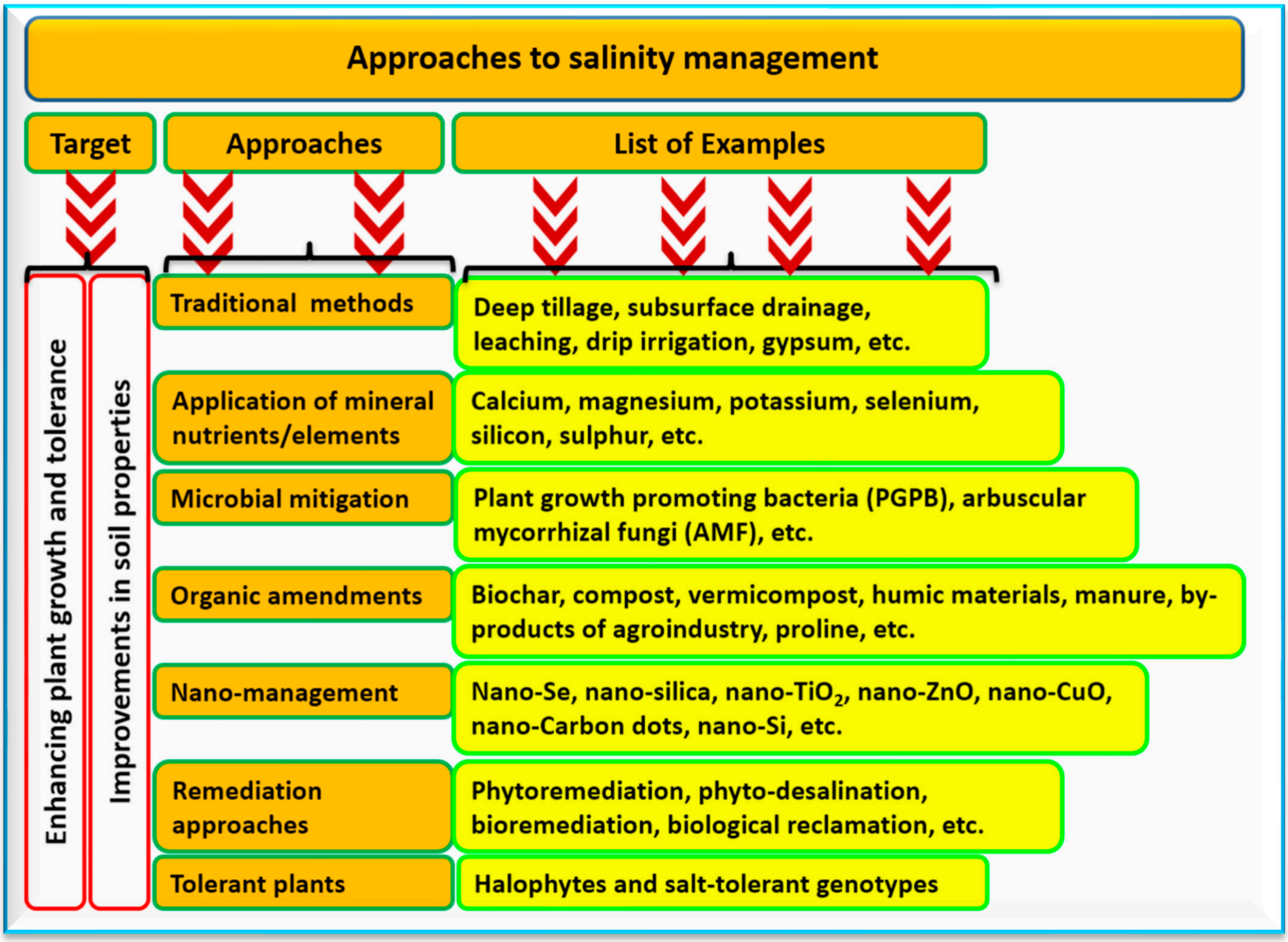
Mapping salt-affected soils using traditional soil survey techniques can be difficult [101,102]. The combination of geographic information systems (GIS) with geospatially referenced remote and/or proximal sensing techniques and spatial statistics has opened new opportunities in the delineation of such soils [103,104], which in turn has promise for improving crop production [105]. Electromagnetic induction (EMI) and electrical resistivity (ER) are the most common proximal sensing techniques used to map salt-affected soils [2]. EMI induces eddy current loops in the soil using an electromagnetic field to determine the apparent electrical conductivity (ECa). A major advantage of EMI is that it does not require soil contact [106]. The combination of EMI data with models to convert the ECa values to measures of soil salinity or sodicity and spatial statistics within a GIS can allow for accurate horizontal and/or vertical representations of the salt content in soils [102,106]. Electrical resistivity is the inverse of ECa. Resistivity data are collected using electrodes that contact the soil to measure the drop in electrical potential. The spacing between electrodes influences the depth to which data are collected, and multiple electrodes on one instrument can collect data at multiple depth intervals. Electrical resistivity is the oldest and probably most widely used proximal sensing technique to determine soil salinity [107].

Remote sensing uses a variety of air- and space-based platforms to collect spatiotemporal environmental data. Platforms such as Landsat, Sentinel 1 and Sentinel 2, MODIS, Advanced Land Observing Satellite (ALOS), and Phased Array L-Band Synthetic Aperture Radar (PALSAR) have been used to successfully map soil salinity. Remote sensing techniques are often combined with other data sources, such as topographic information, an analysis of soil samples from select locations in a study area, data on land use and land cover provided by, for example, the European CORINE database [104], or proximal sensing data such as EMI [108]. It is common to use indices based on spectral bands to map soil salinity. The use of vegetation indices (VI) such as NDVI, SAVI, ARVI, SARVI, and EVI is common, and salinity indices (SI) have also been developed [108]. Machine learning regression techniques and environmental covariates have been employed to improve on soil salinity mapping and modeling with both proximal and remote sensing [108,109]. Proximal and remote sensing approaches provide much more data for a lower cost than traditional field sampling and laboratory analysis approaches, which is a decided advantage. However, the ground-truthing of proximal and remote sensing data remains crucial, as these techniques provide a composite of soil and other environmental factors and therefore are not able to completely replace field sampling, descriptions, and laboratory analysis of soils [104,106,110].

7. Salt-Affected Soil Management

Salinity has deleterious effects on the soil–plant system, which reduces agro-productivity. Soil salinity management is a great challenge facing all countries that have salt-affected soils (Figure 6). There are many approaches for soil salinity management including the traditional methods (deep tillage, subsurface drainage, leaching, drip irrigation, gypsum application, etc.) and the application of mineral nutrients/beneficial elements, microbial, agents and nanomaterials [1,50]. There are approximately 952 million ha of salt-affected soils globally (Figure 7), which represents about 33% of global agricultural land potential [111]. Management is important to crop production in these soils. In general, the suggested approaches to soil salinity management can be classified into the following groups [50]:

1. Physical approaches (e.g., deep tillage, leaching, subsurface drainage, etc.)
2. The application of inorganic nutrients (e.g., K, Ca, Mg, Se, Si, etc.)
3. Microbial mitigation such as plant growth promoting microbes (PGPM), arbuscular mycorrhizal fungi (AMF), etc.
4. Organic amendments (biochar, compost, vermicompost, humic substances, etc.)
5. Nano-management (nano-Se, nano-Si, nano-TiO_2, nano-ZnO, nano-CuO, nano-C dots, etc.)
6. Remediation approaches (phytoremediation, phyto-desalination, bioremediation, biological reclamation, etc.)
7. The growth of salt-tolerant crops, which mainly depends on plant species.



Approaches to salinity management

Target	Approaches	List of Examples
Enhancing plant growth and tolerance Improvements in soil properties	Traditional methods	Deep tillage, subsurface drainage, leaching, drip irrigation, gypsum, etc.
	Application of mineral nutrients/elements	Calcium, magnesium, potassium, selenium, silicon, sulphur, etc.
	Microbial mitigation	Plant growth promoting bacteria (PGPB), arbuscular mycorrhizal fungi (AMF), etc.
	Organic amendments	Biochar, compost, vermicompost, humic materials, manure, by-products of agroindustry, proline, etc.
	Nano-management	Nano-Se, nano-silica, nano-TiO_2, nano-ZnO, nano-CuO, nano-Carbon dots, nano-Si, etc.
	Remediation approaches	Phytoremediation, phyto-desalination, bioremediation, biological reclamation, etc.
	Tolerant plants	Halophytes and salt-tolerant genotypes

Figure 6. Different ways to approach management of salt-affected soils, including traditional and modern methods. Sources: [1,50].

Plants have ways to cope with soil salinity via alterations in phyto-biochemical pathways and changes in chromosomal structures, depending on the degree of adaptation, to reduce salinity stress [1]. Mitigation may include stimulating the antioxidant enzymes (e.g., ascorbic peroxidase, catalase, polyphenol oxidase, glutathione reductase, peroxidase, superoxide dismutase, etc.), inducing phyto-hormones (e.g., cytokinin, ethylene, jasmonate, abscisic acid, etc.), regulating ion uptake (mainly Na^+), modulating the photosynthetic pathways, and promoting osmolyte biosynthesis such as proline, polyamines, and glycine betaine [1]. Highly complex mechanisms protect the main processes in plants, such as respiration, photosynthesis, and water uptake [1]. This section will discuss the management of salt-affected soils, nutrient application, microbial and organic amendments, and nano-management of soil salinity.

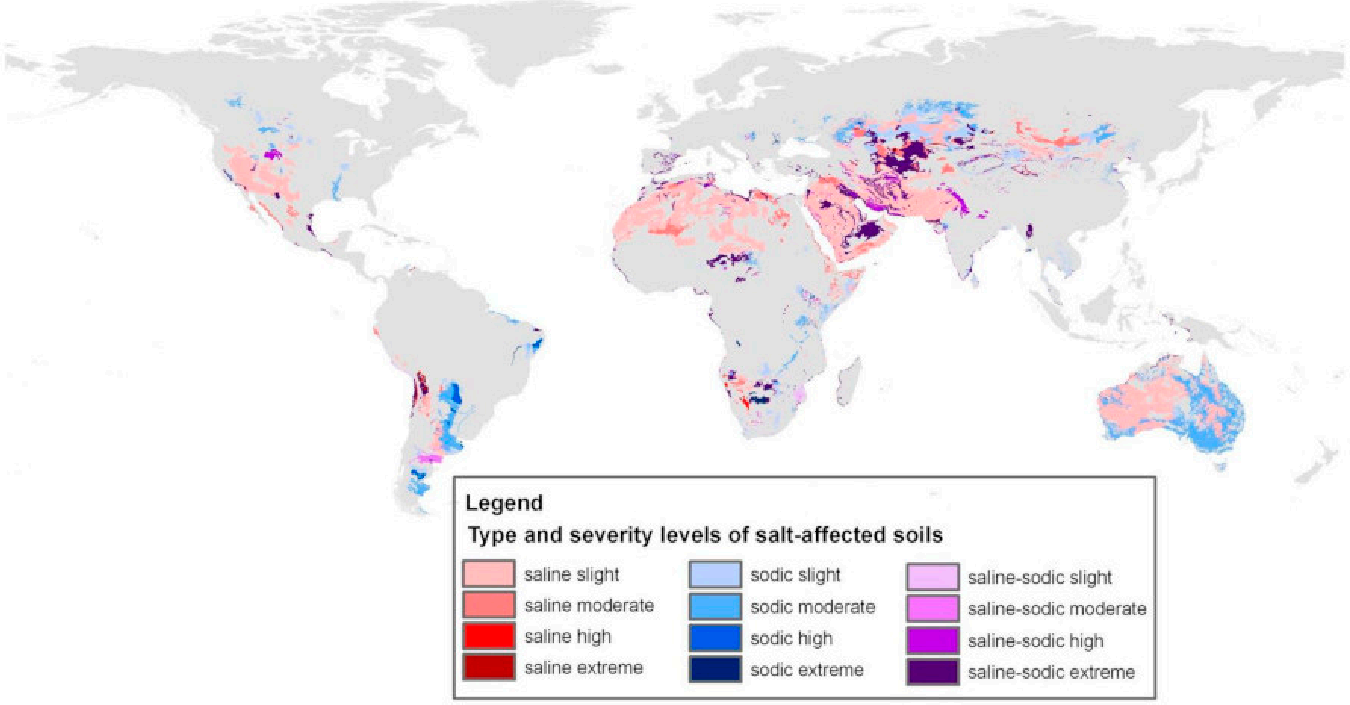


Figure 7. Global distribution of salt-affected soils. Reproduced from [112] with permission from the Royal Society of Chemistry.

7.1. Reclamation of Salt-Affected Soils

There are multiple ways (techniques) of using high quality water for salt washing, and numerous studies address this issue. With flushing, the primary goal is to dissolve salts off the soil surface and allow them to run off the affected field with the water. When leaching, the goal is to move salts through the soil profile so that they are below the rooting zone. Leaching also requires a subsurface drainage system that prevents water from moving back into the root zone through capillary rise and bringing the salts back with it [2]. There are negative environmental effects from flushing and leaching. The water used to flush or leach salts from soil can increase salinity in the rivers that water is discharged to [113], and important plant nutrients such as K, Ca, and Mg can be leached from the soil as well [2].

Sodic and saline–sodic soils often have poor soil structure due to aggregate dispersion by Na. Therefore, it is important to build the structure using cations such as Ca^{2+} that are typically supplied by gypsum [114] or similar byproducts [115]. The structure allows water to pass through the soil for leaching, and the Na ions displaced from the soil cation exchange sites combine with $SO_4{}^{2-}$ from the gypsum to form leachable Na_2SO_4. The salt-enriched water that moves into local rivers causes the same issues as the flushing or leaching of saline soils, and these techniques are also quite expensive [2].

Phytoremediation is another approach to reclaim or mitigate salt-affected soils. A common theme in phytoremediation is the use of deep-rooted plants with high water demand. These plants lower the water table, which prevents the translocation of salts into the root zone via capillary rise. A wide range of plants have been used for this, from a variety of grasses to alfalfa, shrubs, and trees. A major advantage of phytoremediation is the ability to get food, feed, firewood, and other economically beneficial products from the land as it is being remediated [1].

More recent research into salt-affected soil remediation has sought to take advantage of capillary rise to bring salts to the soil surface where they can then be removed. This has been accomplished using crystallization inhibitors and wicking materials. Crystallization inhibitors placed on the soil surface induce salt crystal growth at the surface. These crystals can then be removed, effectively removing salts from the soil. Wicking materials have fine pores that move water into the wicking material via capillary action. The water then evaporates, leaving its salts in the wicking material, which can be removed from the site. While both crystallization inhibitors and wicking materials have shown promise in laboratory studies, there is a need for field experiments to evaluate the applicability of these methods in agricultural and other field settings [116].

7.2. Nutrients for Salt-Affected Soil Mitigation

Plant nutrients and beneficial elements can be utilized to mitigate the effects of saline soil. Essential nutrients for plant growth such as K, S, Ca, and Mg are frequently used, as are beneficial nutrients like Si and Se. The main ways that nutrients mitigate salinity stress are summarized in Table 2. These mechanisms involve (1) reducing the uptake of Na^+ by plant roots and reactive oxygen species (ROS) accumulation, (2) increasing the activity of enzymatic antioxidants, e.g., catalase (CAT), superoxide dismutase (SOD), ascorbate peroxidase (APX), and glutathione reductase (GR), (3) preventing membrane degradation and osmotic injury, (4) enhancing photosynthetic pigment contents (chlorophyll and carotenoids), and (5) upregulating antioxidant enzyme encoding genes [117]. Applied nutrients can also support cultivated plants under irrigation with saline water, as has been reported for alfalfa [118], onion [119], and dry bean [120].

Table 2. The role of selenium and silicon in mitigating salt stress in soil, irrigated water, and exogenous salt stress.

Plant Species	Applied Nutrient Dose	Salinity Level	Effects	Refs.
Squash (*Cucurbita pepo* L.)	Foliar Se (24 mg per plot = 16.5 m^2)	EC = 9.45 dS m^{-1}	Minimized ROS; reduced Na^+ uptake; improved photosynthetic capacity, leaf integrity, nutrient homeostasis; enhanced antioxidant enzymes (CAT, SOD) and enzymatic gene expressions; and regulated Na^+ homeostasis	[117]
Dry bean (*Phaseolus vulgaris* L.)	Foliar Se at 5 and 20 ppm	Irrigation water at EC = 0.6, 1.6, 3.0, and 4.8 dS m^{-1}	Se foliar application can reduce negative impacts of salinity during dry bean production which may differ in case of seed coating or direct application to soil. The applied foliar Se at 5 ppm was better than 20 ppm in improving plant growth under salinity stress	[120]
Pea (*Pisum sativum* L.)	Calcium silicate (14% Si)	Exogenous salt at 5 dS m^{-1} NaCl	Si promoted high soluble protein content, plant biomass, and yield because it reduced Na^+ transport	[121]
Cucumber (*Cucumis sativus* L.)	1.5 mM Si as K_2SiO_3	Exogenous salt at 75 mM NaCl	Si inhibited salt stress by reducing shoot Cl^- and Ca^{2+} contents in cucumber shoot seedlings grown in deep water culture	[122]

Table 2. *Cont.*

Plant Species	Applied Nutrient Dose	Salinity Level	Effects	Refs.
Watermelon (*Citrullus lanatus* L.)	Silicon (4 mM)	Saline water at 3 dS m^{-1}	Combined arbuscular mycorrhizal fungi and Si promoted growth, antioxidant enzyme activities, yield parameters, and pigment and mineral content	[123]
Cucumber (*Cucumis sativus* L.)	Silicon at 200 mg L^{-1}	EC = 4.49 dS m^{-1}	Si mitigated salinity under heat stress by increasing Si content in leaves; regulating water losses via transpiration, and increasing the uptake of N, P, K, Mg, and Se	[24]
Sweet basil (*Ocimum basilicum* L.)	Foliar and soil Si applied at 100 ppm	Salt applied at 1.5, 3.0, 6.0, and 9.0 g NaCl kg^{-1} soil	Applied Si maintained photosynthetic pigment, water status, ion homeostasis, redox status; alleviated oxidative injury; and upregulated antioxidant enzymes	[124]
Strawberry (*Fragaria* × *ananassa* Duch.)	Se applied at 1 mg L^{-1} (Na_2SeO_4)	Salt applied at 40 mM NaCl	The combined application of H_2S + Se inhibited free radicals by 84%, promoted vitamin C, anthocyanin, and antioxidants (CAT, SOD, POX) content, reduced MDA content, and protected the photosynthetic system	[125]
Millet (*Panicum miliaceum* L.)	Se at 1, 5 and 10 µM as Na_2SeO_3	150 mM NaCl	Se enhanced antioxidant enzymes (SOD, CAT, APX, and GR), decreased H_2O_2 content, and regulated Na^+ transporters	[126]
Faba bean (*Vicia faba* L.)	Foliar Se at 2.5, 5.0, 7.5, and 10.0 mg L^{-1}	EC = 6.26 dS m^{-1}	Se at 5 mg L^{-1} alleviated plant oxidative stresses, produced the highest yield and related components and had the greatest nitrogenase activity and lowest MDA values	[13]

Abbreviations: Reactive oxygen species (ROS), malondialdehyde (MDA), catalase (CAT), superoxide dismutase (SOD), and peroxidase (POX), ascorbate peroxidase (APX), glutathione reductase (GR), electrical conductivity (EC).

Many plant nutrients and beneficial elements have been reported to be effective in the mitigation of salt stress in nano form, including selenium, silicon, titanium oxide, and zinc oxide. Silicon can alleviate salinity stress by enhancing tolerance mechanisms at different plant growth stages of deposition or uptake as mono-silicic acid [127]. Many reviews have documented silicon's role in combating salt stress such as mediating crop response to salinity [128], enhancing biochemical and physiological processes in plants [129], supporting rhizospheric microbe communities [130], and alleviating drought and salinity stress in crops [130,131]. Alleviating salt stress with Si can be achieved by decreasing lipid peroxidation and oxidative stress and improving ion homeostasis and photosynthetic ability [129]. Other plant nutrients and beneficial elements exhibit similar behaviors, including potassium [132], selenium [133], and calcium [80].

7.3. Microbial Mitigation of Salt-Affected Soil

The rhizosphere is a crucial biological hotspot in soil. Biological activities in the rhizosphere include many microbial and plant enzyme activities, and the microbial counts are enormous. Typical populations in rhizospheric soil are 10^9, 10^7, 10^6, and 10^3 bacteria, actinomycetes, fungi, and algae per gram of soil, which is around 50–100 times higher than the bulk soil [134]. Soil microbes can support cultivated plants in their mitigation of salinity stress (Table 3; Figure 8). These soil microbes may include arbuscular mycorrhizal fungi (AMF), *Trichoderma* spp., *Serendipita indica*, *Enterobacter* spp., *Bacillus* spp., *Pseudomonas* spp., and others [8]. Soil mitigation, remediation and restoration of salt-affected soils using microbes have received considerable attention. Several organic amendments (e.g., farm manure, biochar, and bio-organic fertilizers) have the ability to alleviate soil salinization by increasing the complexity of microbial networks, altering plant responses to salt-affected soils [75]. The role of halotolerant rhizobacteria in the mitigation of soil salinity stress also has certain mechanisms, which may include improving the photosynthesis rate, producing antioxidants, facilitating the accumulation of osmolytes, decreasing Na^+ ions, maintaining water balance, enhancing the germination rate, and maintaining well-developed plant fractions (e.g., roots and shoots) under salinity stress conditions [135]. The ameliorative impact of bio-organic fertilizers for crop production in salt-affected soils has also been demonstrated, e.g., in [19,136]. PGPB can support cultivated plants under salinity stress by degrading ACC (the enzyme 1-aminocyclopropane-1-carboxylic acid) deaminase, which acts as a precursor of ethylene in all higher plants. The mechanism of salt stress tolerance might be linked to the synergetic functioning of ACC deaminase, which produces bacilli as bioinoculants and facilitates the accumulation of trehalose [137]. More studies on the contribution of PGPR to salinity stress tolerance in crops can be found in [138–140].

Table 3. Response of soil microbial communities to soil salinity under different agricultural practices or environmental conditions, as reported in some studies published during the first half of 2023 regarding plants grown in salt-affected soils.

Main Microbes	Environmental Conditions	Main Findings	Refs.
Bacterial and fungal communities	Salinized grassland soils (pH 9.31 and EC 3.93 $dS{\cdot}m^{-1}$)	Natural restoration decreased the salinity of grassland soils (pH to 8.32 and soil EC 1.36 $dS{\cdot}m^{-1}$), improved soil fertility and the abundance of bacterial and fungal phyla *Acidobacteria* increased, whereas *Ascomycota* decreased, respectively.	[141]
Bacteria and fungi	Coastal salt marsh ecosystem in a microcosm experiment	*Bacilli* had high salt tolerance, while *Bacteroidota* was more sensitive. SOM can regulate salt stress by controlling microbial activities, metabolism, and C-sequestration in coastal salt marshes.	[142]
Fungal decomposers	Soil microcosm study incorporating wheat and maize straws under salinity stress	Straw increased soil DOC, SOC, $NH_4{}^+$-N and MBC contents but reduced $NO_3{}^-$-N, and fungal diversity. It strengthened the fungal decomposers *Cephalotrichum* and *Coprinus* and *Schizothecium* under light and severe salinity	[143]
Soil microbial community	Abandoned salinized farmland	The reclamation of abandoned salinized farmland can be promoted by the activity of soil microbes by improving soil's physical properties (FC, Ks, BD), nutrient status, and microbial metabolic activity (CAT and UR)	[89]
Prokaryotic dominated community	Climate-smart land use in arid saline soils	Treated wastewater irrigation amended with gypsum promoted the cropping system (switchgrass and sorghum) due to a copiotroph-dominated prokaryotic community and the buildup of SIC and SOC stocks for C-sequestration	[85]
Halophilic micro-organisms	Saline soils in semi-arid and arid Mediterranean regions	Sustainability in marginal reclaimed soils under Mediterranean climate can be achieve with plant-based technologies and soil halophytes (bacteria and AMF)	[50]

Table 3. *Cont.*

Main Microbes	Environmental Conditions	Main Findings	Refs.
Soil bacterial and fungal community	Salt-affected anthropogenic alluvial soil (field experiment)	Vertical rotary tillage mitigated soil salinity by increasing salt leaching, macro-aggregates, and organic carbon. Soil microbial communities shifted through the evolution of microbes better adapted to the altered micro-habitats.	[144]
Soil microbial community	Coastal saline–sodic soil polluted with microplastics	Microplastic type, dose, and size decreased soil microbial diversity (fungi are more sensitive than bacteria). Polyethylene had a stronger negative impact than polypropylene on the saline–sodic soil ecosystem.	[145]
Soil bacterial community	Salinized soil polluted with dibutyl phthalate	Pollution and salinity stress changed the structure/composition of the bacterial community, soil invertase and β-glucosidase enzyme activity, and soil C cycle.	[146]
Soil bacterial (B) and fungal (F) community	Saline–sodic soil	Lignite bioorganic fertilizer promoted soil microbial communities (B+F), stability, functions, Ks, and sunflower–microbe interactions by altering core rhizo-microbiomes under saline–sodic conditions	[84]
Actinomycetes and fungal community	Salinized oil-polluted coastal soils	Bio-amendments (biochar, SMS) enhanced the degradation of crude oil pollution by enhancing bio-stimulation, bio-augmentation, mitigating microbial community abundance, and promoting physical/chemical properties of the soil	[94]
Soil bacterial community	Salinized soil in a microcosm experiment	Integrated microbial approach for sustainable P and soil salinity management through integrated utilization of P-accumulating bacteria and P-solubilizing bacteria via P-leaching by promoting soil aggregation and alkaline phosphatase levels	[82]
Halophilic bacteria	Saline–sodic soil	Applying marlstone and cultivating Jerusalem artichoke reduced salinity stress by increasing halophilic bacteria (e.g., *Thioalkalivibrio* and *Thiohalobacter*), DOC, N-fixation capacity, and soil aggregates	[147]

Abbreviations: dissolved organic C (DOC), soil organic C (SOC), microbial biomass C (MBC), bulk density (BD), saturated hydraulic conductivity (Ks), field capacity (FC), catalase (CAT), urease (UR), soil inorganic carbon (SIC), arbuscular mycorrhizal fungi (AMF), spent mushroom compost (SMS).

7.4. Organic Amendments

Organic amendments applied to salt-affected soils (i.e., saline, sodic, and saline–sodic soils) have been effective in mitigating soil salinity stress for plants and microorganisms. Several kinds of organic amendments have been utilized, such as compost, manure, and biochar, all of which represent crucial sources of SOM which increase the complexity of microbial networks and promote nutrient uptake by plants and soil microbial activity in salt-affected soils [75]. The mitigation of soil salinity stress with organic amendments has been reported with biochar and its composite materials e.g., in [80,148–150]. Examples of the effects of biochar and its combination with other amendments on cultivated plants under salt stress are shown in Figure 9. There are many modified biochar (BC) forms, including ordinary BC, nanoparticle (NP)-sized BC, acidified BC, and acidified NP-BC [151]. To improve crop production in salt-affected soils, it is recommended that biochar be applied in combination with other amendments such as BC + fertilizers [152], BC + titanium gypsum [80], sulfur-modified BC [153], Ca-modified BC [154], BC and polyacrylamide [155], Fe-modified BC [152], silica modified BC [156], BC and humic acid [157], and BC-based nanocomposites [158].

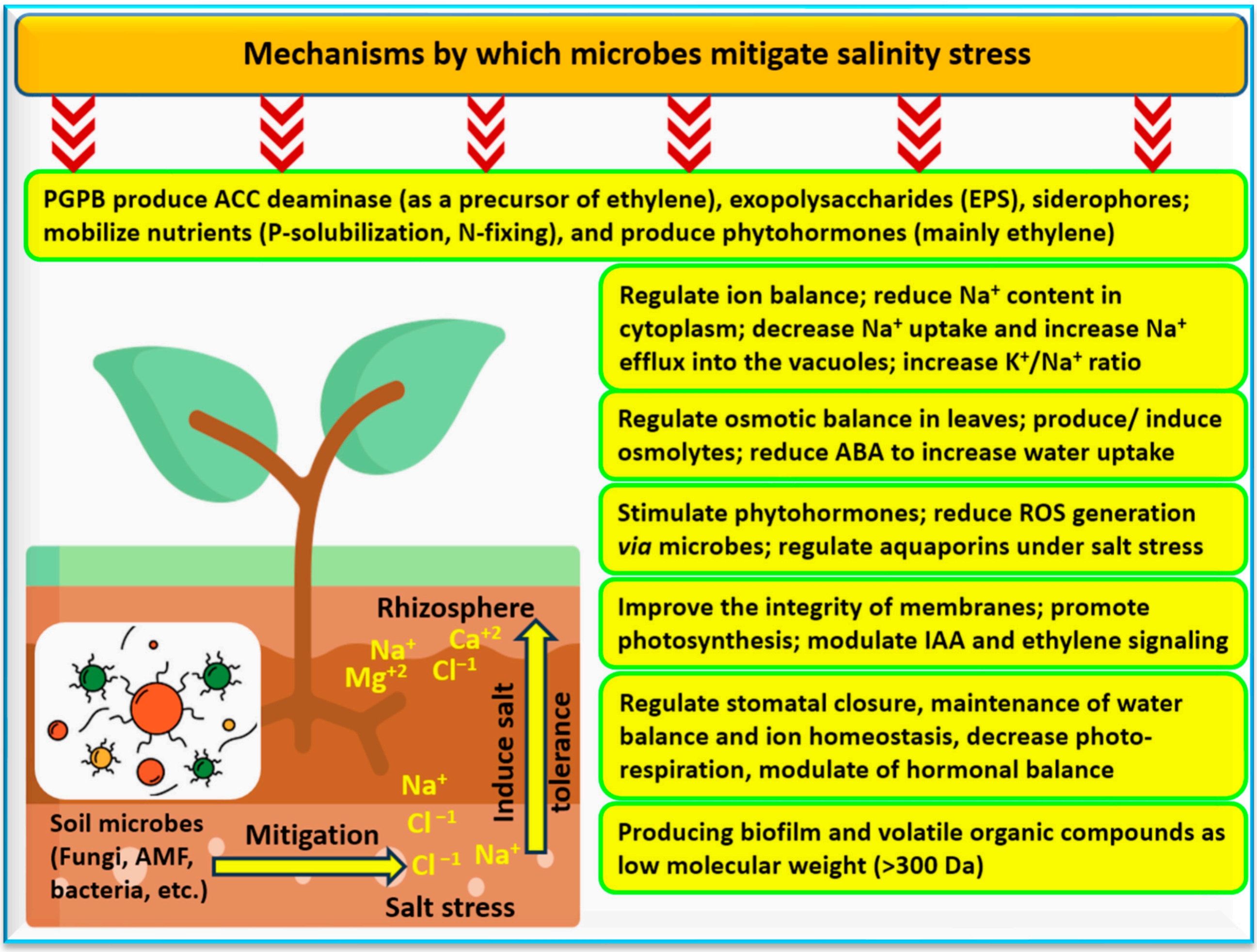


Figure 8. Mechanisms by which microbes enhance plant salt tolerance [8,50,139]. Abbreviations: plant growth-promoting bacteria (PGPB); 1-amino-cyclopropane-1-carboxylic acid (ACC). Images from https://www.flaticon.com/free-icon/, accessed on 22 September 2023.

7.5. Nano-Management of Salt-Affected Soils

Soil salts cause deleterious impacts on crop productivity due to oxidative stress that results from the generation of ROS. This weakens the plant's defense system, causing lipid peroxidation, plasma membrane destruction, and DNA deterioration [27]. Nanomaterials have been shown to be anti-stressors and can mitigate soil salinity stress through multiple mechanisms (Figure 9). These mechanisms may include improving the ability of stressed plants to retain K^+ and exclude Na^+, producing nitric oxide, maintaining ROS homeostasis, increasing α-amylase activity, and decreasing lipoxygenase activity [159]. Examples of the role nanomaterials have in mitigating salt stress are presented in Table 4. The application of nanomaterials to promote tolerance in stressed plants has received a great deal of attention recently. Nanomaterials have shown potential as an effective, economical, and sustainable approach for efficient agro-production. Nanomaterials have the ability to increase plant tolerance to salt by protecting the photosynthesis process, detoxifying ROS, and alleviating ionic and osmotic stress [159]. Nanomaterials that have been investigated to improve the tolerance of salt-stressed plants include nano-selenium [28], nano-gypsum [29], nano-biochar [158], silica nanoparticles (NPs) [26], cerium oxide NPs [160], carbon nanodots [30], titanium dioxide NPs [161], carbon nanotubes [162], and nano-zinc [15]. In general, nanomanagement has become an important approach in modern farming to reduce stresses such as salt stress [163], drought stress [164], and soil degradation stress [165], and has been shown to be a possible sustainable solution for the mitigation of climate change [166].

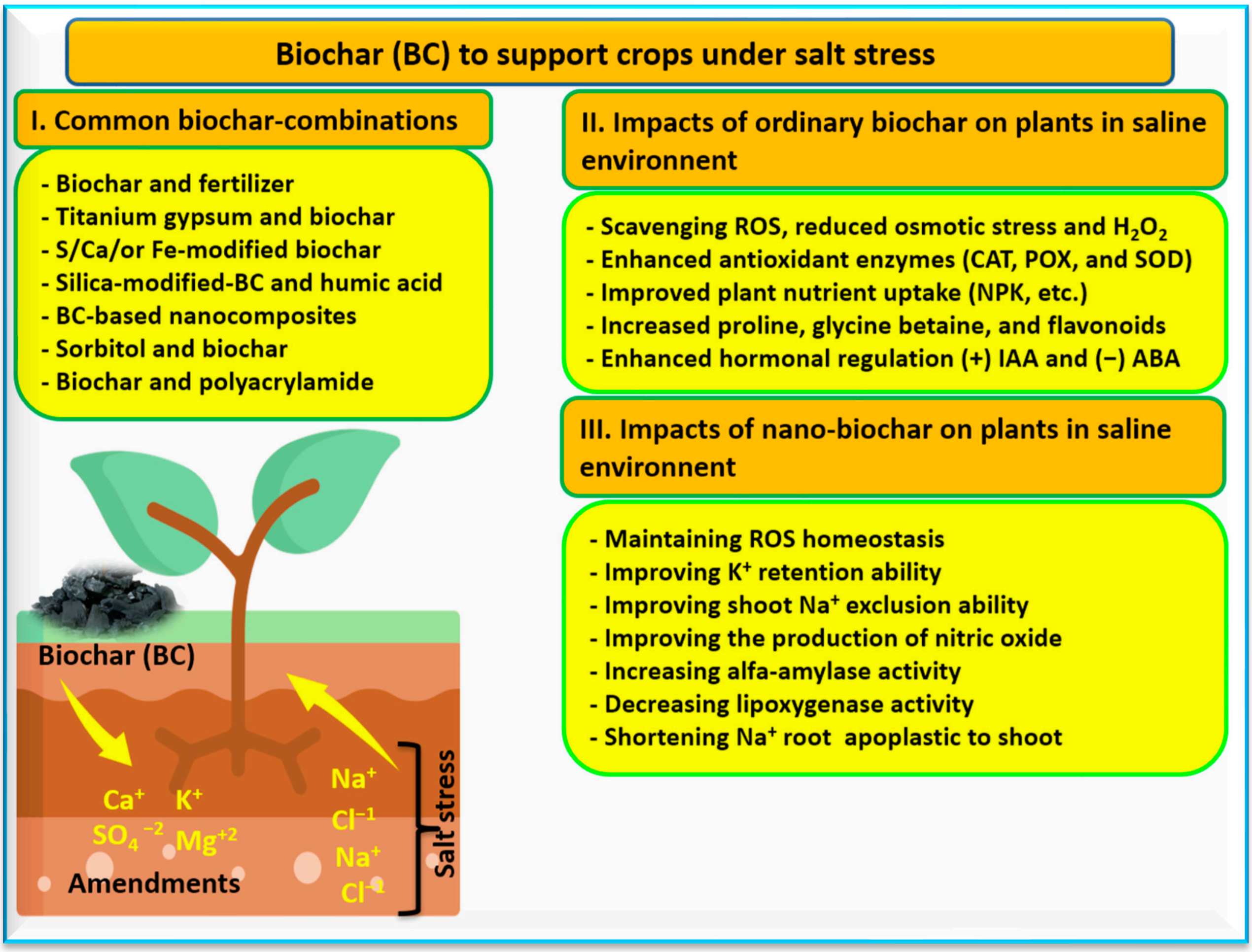


Figure 9. Impact of biochar (including nano forms) and its combination with other amendments on mitigating plant stress in salt-affected soils. Sources: [150,159]. Images from https://www.flaticon.com/free-icon/, accessed on 22 September 2023.

Table 4. Examples of the roles nanomaterials (nanonutrients) can take in mitigating salt stress.

Plant Species	Nanomaterial Dose	Soil Conditions	Suggested Effects	Refs.
Safflower (*Carthamus tinctorius* L.)	BNC-MgO + BNC-MnO at 25 g kg^{-1} soil	EC = 6 and 12 dS m^{-1}	Nanocomposites improved the growth of roots and shoots by enhancing nutrient uptake by plants, lowering soil SAR, ESP, and osmotic stress, and decreasing salt toxicity	[167]
Rice (*Oryza sativa* L.)	Foliar-applied Si-NPs (20 mg L^{-1})	Salts at 100 mM	Exogenous Si-NPs alleviated salt stress toxicity and promoted carotenoids, chlorophyll content, total soluble protein content, and antioxidants (CAT, SOD, POX); Si-NPs protected plants from oxidative stress by triggering the expression of HKT genes	[168]

Table 4. *Cont.*

Plant Species	Nanomaterial Dose	Soil Conditions	Suggested Effects	Refs.
Common bean (*Phaseolus vulgaris* L.)	Bio-Si-NPs (2.5 and 5.0 mmol L^{-1})	EC = 7.8 dS m^{-1}	Bio-Si-NPs at 5 mmol L^{-1} decreased malondialdehyde, electrolyte leakage, and heavy metals (Pb, Cd, and Ni) in leaves and pods of beans compared to the control grown on polluted saline soils	[169]
Cucumber (*Cucumis sativus* L.)	Bio nano-Se at 25 mg L^{-1}	EC = 4.49 dS m^{-1}	Bio nano-Se increased K^+ content in leaves, regulated osmotic balance, and controlled stomatal opening under both soil salinity and heat stresses	[24]
Rapeseed (*Brassica napus* L.)	ZnO-NPs at 25, 50, and 100 mg L^{-1}	Salts at 150 mM	ZnO-nano-priming enhanced the development of seedlings via reducing ROS accumulation, the biosynthesis of pigments, osmotic protection, increasing antioxidant enzymes, and enhancing economic yield under saline conditions	[170]
Rapeseed (*Brassica napus* L.)	Se (IV) or bio-Se-NPs at 50, 100 and 150 µmol L^{-1}	Salts at 150 and 200 mM	Biological Se-NPs were preferable in improving phenotypic attributes, germination rate, photosynthetic efficiency and osmolyte accumulation versus Se (IV) for seedlings without any toxicity under salt stress	[171]
Rice (*Oryza sativa* L.)	Zinc sulphate NPs (5 and 10 mg kg^{-1} soil)	Saline–sodic soil	$ZnSO_4$-NPs (10 mg kg^{-1}) were recommended to promote rice growth and yield under salinity stress due to improved soil chemical properties (SAR and pH), uptake of nutrients, and enhanced physiological attributes	[27]
Maize (*Zea mays* L.)	Nano-rock phosphate at 1140 P kg ha^{-1}	Reclaimed soil (pH 8.39, ECe 3.84 dS m^{-1})	Suitable P-solubilizing bacteria increased the efficiency of nano-rock phosphate by promoting P-mobilization and/or solubilization and increasing root carboxylate secretions and P-biochemical fertility due to decreased rhizosphere pH	[172]
Tomato (*Solanum lycopersicum* L.)	Functional carbon nanodots at 8 and 16 mg kg^{-1} (FCNs)	Saline–sodic stress (EC = 4.9 dS m^{-1})	The nano form alleviated stress on tomato growth and productivity due to the up-regulating of photosynthesis, increasing antioxidants, enhancing osmotic adjustment, promoting uptake of nutrients, increasing soil enzyme activities, and decreasing soil pH and salinity	[30]
Pumpkin (*Cucurbita pepo* L.)	Nano-priming with TiO_2 (60 ppm)	Irrigated with saline–sodic water (5.2 dS m^{-1})	Nano-priming resulted in the highest values of proline, SOD, TAC, and K^+/Na^+, respiration, and the lowest values of Na^+ and MDA under saline soil (4.8 dS m^{-1})	[173]

Table 4. *Cont.*

Plant Species	Nanomaterial Dose	Soil Conditions	Suggested Effects	Refs.
Maize (*Zea mays* L.)	Nano-soaking (40, 60 and 80 ppm) of TiO_2-NPs	200 mM NaCl in a culture system	Nano-priming at 60 ppm was the most effective dose to mitigate salt stress on seedlings by increasing K^+ uptake, the relative water content, total phenolic and proline contents, and SOD, CAT, and PAL activities	[174]
Strawberry (*Fragaria* × *ananassa* Duch.)	ZnO-NPs (15 and 30 mg L^{-1})	Salts at 35 and 70 mM	15 mg L^{-1} alleviated stress by decreasing accumulated toxic ions and increasing CAT, POX, K^+ uptake, proline content, and leaf anatomical features	[175]

Abbreviations: Total antioxidant capacity (TAC), malondialdehyde (MDA), superoxide dismutase (SOD), phenylalanine ammonia lyase (PAL), biochar-based nanocomposite (BNC), electrical conductivity (EC).

8. Crop Response to Soil Salinity and Mechanisms

Salts in soil have detrimental effects on functional processes in both soil and plants. Soil physico-chemical (e.g., BD, infiltration, aeration, soil water potential, soil aggregates, soil fertility) and biological (e.g., soil enzyme and microbial activity and biodiversity) properties are negatively impacted by high soil salt content [2,176]. Salt-affected soils cause biochemical, physiological, and molecular alterations in crops (Figure 10) [1,177]. The negative impacts of salt-affected soils on crop production can be mitigated through soil management techniques. Many of these techniques are focused on enhancing soil properties, such as soil structure and soil nutrient ratios. Amendments applied to the soil to achieve this include gypsum and related compounds [76], biochar [154], compost [52], earthworms [178], microbial inoculants [50], vermicompost [79], and electro-remediation [179]. Other approaches to improve plant response to salinity stress include afforestation [180], seed priming [173], genetic improvements to crops [181], using crops that are salt tolerant (halophytes) [50], and agroforestry [182]. Some approaches depend on utilizing both soil and plant management in a synergic manner [50].

Several mechanisms have been suggested to explain how plants are able to mitigate stresses imparted by soil salts [40]. The pathway of any suggested mechanism primarily depends on the applied materials and management approaches used. However, certain groups of physiological, biochemical, and molecular plant attributes are responsible for driving these mechanisms. In general, the mechanisms include activating the osmotic stress pathway, regulating ion homeostasis, mediating plant hormone signaling, and regulating the cell wall composition [36,40,43,183,184]. Si-NPs have been shown to alleviate salinity stress in rice plants by triggering physiological and genetic repair mechanisms [168]. The plant gene transporters of both Cl^- and Na^+ are linked with salinity tolerance which may vary from species to species and/or even within cultivars [185]. The control of Cl^- uptake and its translocation in plants is due to slower loading into the xylem, root efflux, and intracellular compartmentation [185].

Plant response to salt stress is primarily through ionic and osmotic stress. This leads to the formation of many signals in plants, including the hyperosmolality of Na^+, the accumulation of Ca^{2+}, the activation of ROS signaling, and the alteration of phospholipid composition. These signals can activate plant adaptive processes to alleviate salt stress through maintaining an ion balance and osmotic homeostasis, inducing phytohormone signaling and regulating cytoskeleton dynamics and the cell wall structure [184]. High-affinity potassium transporters (HKTs) have been broadly characterized in different plants and have been shown to play a critical role in salt tolerance by excluding Na^+ ions from the sensitive shoots of plants, mediating Na^+ import due to their transport selectivity, and they may mediate Mg^{2+}/Ca^{2+} permeability across the plasma membrane of plant cells [183].

Therefore, several mechanisms can be illustrated for each applied amendment or approach that are linked to particular genes.

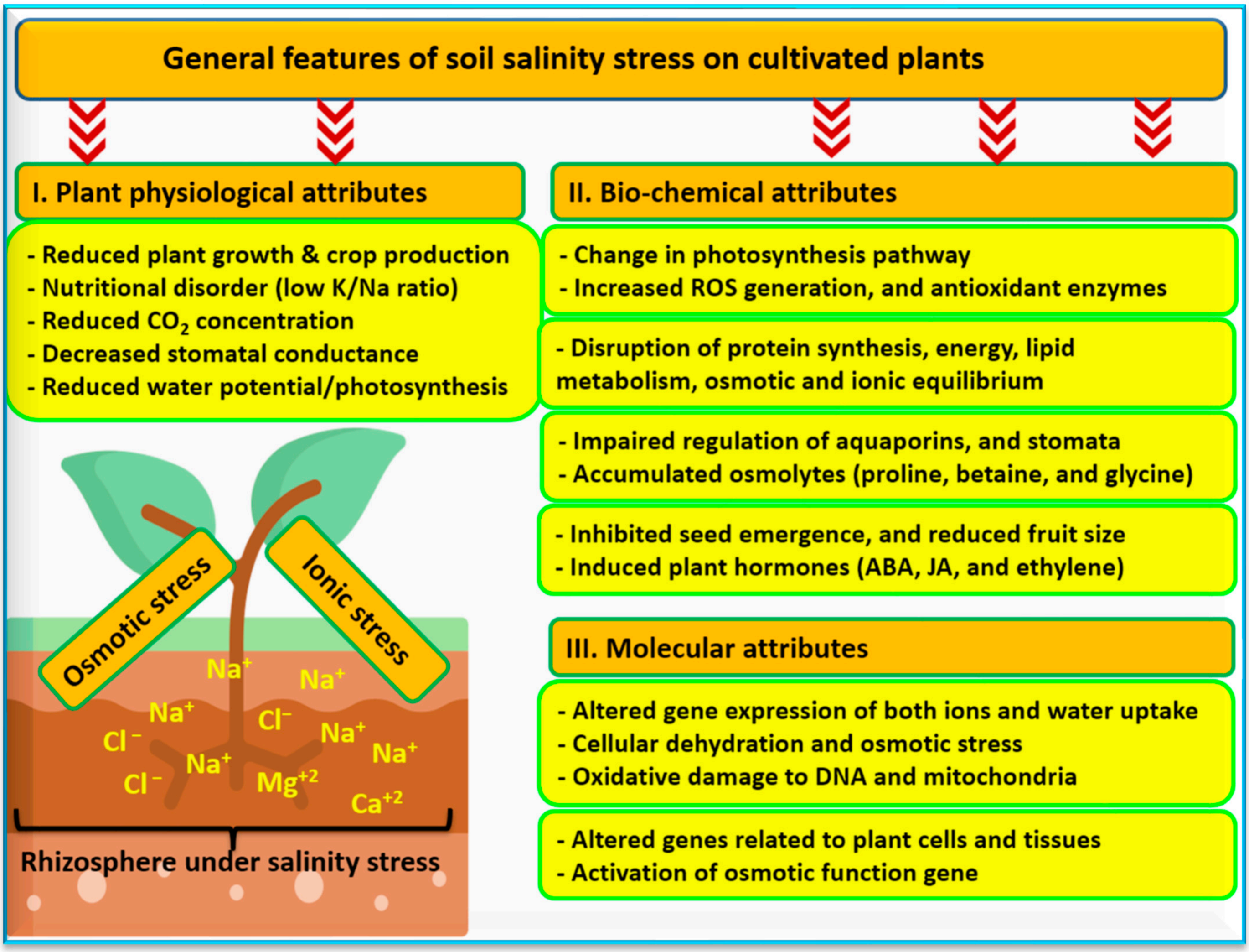


Figure 10. Impacts of soil salinity on cultivated plants, including the physiological, biochemical, and genetic attributes. Sources: [1,135,177].

High concentrations of salt ions can change the ion concentrations in the plant cell wall, which are sensed by specific receptors or sensors such as receptor-like kinases (RLKs) and glycosyl inositol phosphoryl ceramide (GIPC). These sensors can activate signaling pathways such as the salt overly sensitive (SOS) pathway to re-distribute ions and achieve homeostasis [6]. Osmotic potential forms from changes in the balance between ion concentrations inside and outside of plant cells, a process which is monitored by specific sensors such as nicotinamide adenine dinucleotide phosphate (NSCCs), through the high-osmolarity glycerol (HOG) pathway to regulate the synthesis of organic osmolytes (e.g., betaine and proline). Osmotic homeostasis is achieved via the uptake of ions. Plants generate and accumulate ROS through plasma membrane-bound nicotinamide adenine dinucleotide phosphate (NADPH) oxidase under saline conditions, which manages ROS homeostasis through secondary metabolites [6].

9. Conclusions and Future Perspectives

As demonstrated in this review, there is still a crucial need for more information about crop production in salt-affected soils and a number of issues that need additional investigation. These include: (1) Reliable, accurate mapping of global salt-affected soil distribution.

It is important to know the spatial extent of each subtype of these soils (e.g., saline, sodic, and saline–sodic) to allow appropriate management and mitigation efforts to maximize crop production. Proximally and remotely sensed data that are georeferenced with GPS, analyzed with advanced spatial statistical techniques, and mapped with GIS show promise to help with this. (2) Saline soils have historically been determined by measuring electrical conductivity, which is quick, easy to measure, and inexpensive. However, there are many different ions involved in saline soils, and the exact challenges facing crop production depend on the types of ions present and their individual concentrations. Electrical conductivity does not provide this information. There is a need to identify easy and relatively inexpensive methods to provide information on the types and relative abundance of different ions present in saline soils. (3) It is important that we continue to investigate how the soil microbiome can contribute to crop production in salt-affected soils. (4) Nanotechnology shows great promise in promoting crop production in salt-affected soils, but these studies are in their early stages, and both the pros and cons need additional study, including the potential negative environmental effects of the use of nanomaterials. (5) It is possible to remediate salt-affected soils, but traditional techniques based on flooding, leaching, and structure building are often expensive and can create their own environmental issues. Opportunities like phytoremediation, crystallization inhibitors, and wicking materials need additional investigation. It is also important that more innovative research is conducted on salt-polluted soils, such as those impacted by petroleum production.

Crop production under soil salinity faces many global issues, especially in the era of climate change. These issues may impact the production of different crops, both from crop variety (e.g., maize, wheat, rice, etc.) and crop use (e.g., food, energy, and forage crops) perspectives. The global scientific community should work on saving arable lands for these necessities. Sustainable solutions for global food, energy, and water security and the SDGs must be prioritized. These strategies should be built on the nexus of water–energy–food along with a focus on soil security.

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