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Mitigating the impact of soil salinity: recent developments and future strategies

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Highlights

- *Fast and reliable monitoring of soil status can help to promptly adopt strategies to decrease soil sa-linity and/or reduce crops' vulnerability to salt.*
- *Leaching, alternating fresh- and saline water for irrigation purpose and the use of efficient irriga-tion systems can be effective water management strategies against soil salinity.*
- *Mulching and the use of amendments can improve soil status by decreasing its NaCl levels.*
- *The rotation of halophyte and glycophyte plant species can allow NaCl sequestration while main-taining profitable yields.*
- *Saline environments and plants adapted to such environments can be a valuable source of PGPB and AMF which can improve plant tolerance to salinity through multiple mechanisms.*

Abstract

Soil salinity is among the major abiotic stresses that plants must face, mainly in arid and semiarid regions, and high salinity tolerance is an important agronomic trait to sustain food production. Agricultural soils are unstable and subject to changes in salinity level, and monitoring them at both the local and the regional scale is a relevant activity to adopt soil and water management strategies to decrease salt concentration in the root zone, thus minimizing impacts on plant growth and productivity. Additionally, beneficial soil microorganisms such as arbuscular mycorrhizal fungi and plant-growth-promoting bacteria, particularly when sourced in saline environments, can alleviate plant salinity stress by multiple mechanisms. In this review, some interventions aimed at reducing soil salinity will be discussed, as well as interventions aimed at reducing the vulnerability of crops to saline stress to obtain more tolerant plants.

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Introduction

Soil salinization causes the degradation of soil quality, especially in arid and semiarid areas, with an impact on crop productivity. Devkota *et al*. (2022) summarized the existing literature to estimate that approximately 20% of the world's cultivated lands and 33% of irrigated lands are salt-affected. Besides that, irrigated agriculture plays a crucial role in food security, contributing to more than 40% of global food production. In order to respond to the growing demand for food due to the expected increase in world population, it is estimated that by 2030 it will be necessary to expand irrigated areas from 202 million ha to 242 million ha (Devkota *et al.*, 2022). The water demand for food production is greater in arid and semiarid areas, where more than 90% of agriculture depends on irrigation. These areas, which may already be affected by salinity, are very vulnerable to land degradation (Figure 1).

According to Tomaz *et al*. (2020), two types of salinization may be distinguished: primary (natural) or secondary (anthropogenic). Primary salinity is mainly determined by groundwater of marine origin or due to sea salt deposition by wind, seepage, *etc*. In arid and semiarid regions, the high evaporation combined with annual rainfall below 250 mm leads to soil and water salinity. Anthropogenic activities, such as irrigation with brackish water, poor drainage facilities, improper water management, intensive fertilizer use, *etc*., can lead to secondary salinity. Climate change has consequences as regards soil salinity. The rise of greenhouse gases increases air temperature and decreases relative humidity in combination with extreme rainfall events. One of the effects is the increase in the annual soil salinization rate (IPCC, 2013). Climate change can accelerate seawater intrusion into fertile soils due to sea level rise, and groundwater overexploitation for irrigation purposes also increases soil and groundwater salinity (Mukhopadhyay *et al.*, 2021). In Italy, the risk of seawater intrusion is far from remote, and in the summer of 2022, the prolonged drought appears to have led to the intrusion of seawater into the coastal aquifers (Carillo, 2022). Evidence of the sea level rise and associated seawater intrusion has contributed to an increase in soil salinity in Senegal and Bangladesh (Eswar *et al.*, 2021).

In a broader sense, soil salinization is due to the accumulation of salts in the soil, causing soil degradation, affecting crop productivity and the environment with cascading impacts on socio-economic growth and food security, such as lower profit, poverty, farmers' migration, increased fertilizer requirement and a slow-down in land reclamation (Mohanavelu *et al.*, 2021).

Effects of salinity on plants include ion toxicity, osmotic stress, mineral deficiencies, and photosynthetic imbalance, leading to impaired growth and decreased crop yield. In these complex scenarios, with multiple implications in several sectors, it is important to evaluate actions that reduce salinity and mitigate its impact.

Zaman *et al*. (2018) suggested that a combination of mitigation and adaptation is to be applied. Mitigation aims to reduce soil salinity by applying different technologies to farming, *e.g.*, water management and improvement of soil properties. Instead, adaptation comprehends strategies to allow the use of salt-affected soils by adjusting the agronomic management and reducing the crops' vulnerability to salt stress. Possible examples are the cultivation of less sensitive cultivars or the enrichment of beneficial microbiota in the rhizosphere.

This review describes the strengths and weaknesses of the currently available water and soil management techniques for the mitigation of soil salinity, discussing their application in different scenarios and to different crops. The second part of the review focuses on the potential of beneficial microorganisms as a tool to decrease salinity stress in plants, focusing in particular on bacteria and fungi isolated from saline environments. The described tools to contrast and mitigate salinity, which should be implemented one a time or in combination, are summarized in Figure 2.

Reduction of soil salinity

Water management

The technique of leaching is a consolidated practice when the build-up of soluble salts in the soil becomes or is expected to become excessive. It consists of applying an amount of water that exceeds the crop needs during the growing season so that the extra water moves at least a portion of the salts below the root zone by deep percolation to leach the salts from the root zone. Alternatively, in some areas, pre-sowing or post-harvest leaching is applied; in this case, the amount of water is higher than in the leaching applied during the growing season. These techniques suppose that fresh water is available when a farmer requests it and that the areas in which leaching is applied are well drained to avoid secondary groundwater salinization. Most of the time, areas affected by salinity are located in economically undeveloped areas; hence farmers have few financial resources to invest in drainage systems or other interventions that help drain the salts and prevent an increase in groundwater salinity. Besides that, in many salt-affected areas, there can be fluctuations in available fresh water due to weather variability (drought spells) and climate trends. Furthermore, in those areas, fresh water is often managed at the government level, for which the farmer cannot promptly make corrections by applying leaching, exacerbating the problem.

Figure 1. The picture was taken in the agricultural surroundings, coming through the silk road from Lanzhou (city) to Dunhuang (city), Gansu region, Northwest China (credits Anna Tedeschi).

Rainy years refill water reservoirs and dry years reduce the availability of the good quality water needed for leaching applied pre-sowing and/or during the crop cycle. In some areas, climate change has exacerbated the reduction in good-quality water due to the persistence of dry years. On the other hand, even abundant autumn-spring rains (*e.g.*, 800 mm) may not be sufficient to leach the salts from the soil profile. Leaching can occur in the root zone, but with the new irrigation, season salinity may increase again due to upward salt transport by capillary rise and by application of saline irrigation water (Tedeschi and Dell'Aquila, 2005).

Useful contributions about leaching are also summarized by Letey *et al*. (2011), who analyzed the current guidelines for leaching based on steady-state analyses and concluded that the present guidelines overestimate the leaching requirement and the negative consequences of irrigating with saline waters. From this point of view, the scientific communities should consider adjusting the leaching requirement or giving more tools to the farmer to precisely evaluate the leaching requirements.

Other factors, such as soil properties and soil type, should also be considered when applying leaching. In desert areas with silty sand soils, leaching does not face problems of slow infiltration or water ponding, which is frequent in soils with medium-high clay content (Tedeschi and Menenti, 2002). In some soils, mainly clay soils, the salinity forms a hard surface crust that makes both seed emergence and water infiltration difficult. Sustainable saline irrigation management requires a knowledge of the spatial salinity distribution where interventions are needed and also a proper knowledge of the soil's hydrological properties. Monitoring by traditional methods requires frequent sampling, which can be cost-prohibitive, but new technologies like drones and soil sensor probes are increasingly used to monitor soil salt distribution, water consumption, and plant growth. These new tools allow timely corrections in irrigation management in terms of frequency, water quality, and water volume. As Ivushkin *et al*. (2019) reported, up-to-date information on spatial distribution and severity of soil salinity is crucial for agricultural management of affected areas, to reduce, or even avoid, economic losses and restore soil productivity. For these reasons, remote sensing methods are used more and more often for soil salinity monitoring and mapping (Allbed and Kumar, 2013). Different scientific disciplines have studied salinity, and new insights toward better crop and irrigation management have been provided to farmers. Deficit irrigation is an optimization strategy in which water application is smaller than the full crop evapotranspiration requirements. It was presented to farmers as a possible solution when water is scarce or water restriction is applied due to the fact that may lead to an increase in water usage effectiveness and vegetable quality. However, it is important to take into account that it may also impose some degree of yield reduction and increases the risk of soil salinization due to reduced leaching (Machado *et al.*, 2017). Wherever the economic investment is possible, it would be necessary to switch from flooding or furrow irrigation systems to drip irrigation systems. The drip irrigation system is more efficient than the others and it uses less water localized near the plant (Xiukang and Yingying, 2016). Malash *et al*. (2008) compared furrow and drip irrigation systems applied to tomato production under saline conditions. Moreover, they evaluated two different water management strategies: alternating or diluting saline water with non-saline water in different ratios. The authors recommended drip irrigation under saline conditions because fruit yield and yield per unit of water used were higher than when furrow irrigation was applied. In the same study, blending irrigation water provided a better yield than alternating fresh and saline water. Also, Singh and Panda (2012) applied different irrigation strategies to mustard subjected to salinity stress. They concluded that the growth reductions due to saline irrigation are minimized if the application of saline groundwater (7.4 dS m^{-1}) occurs later in the growing season or if this groundwater is mixed with other non-saline water (0.4 dS m^{-1}) earlier in the growing season.

Rahil *et al*. (2013) have studied the effect on the tomato

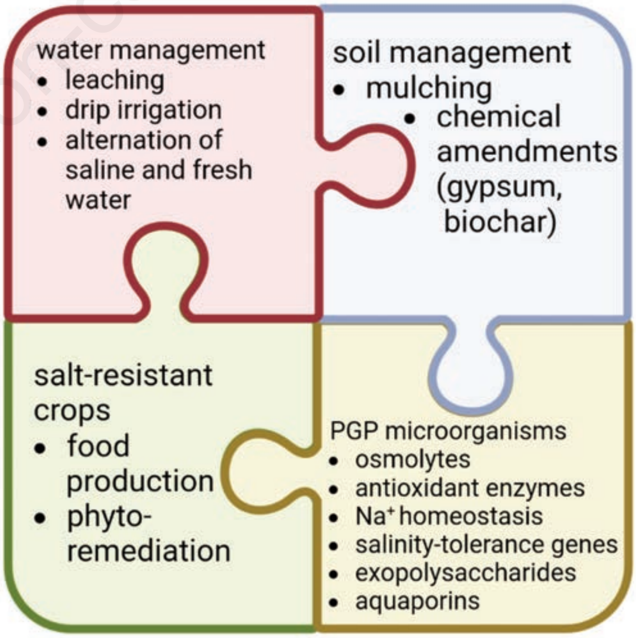

Figure 2. Schematization of the possible approaches for addressing high salinity in agricultural soils.

production of three levels of saline water (3, 5, and 7 dS m^{-1}) for three irrigation frequencies, *i.e.*, every day, every second day, and every three days. Authors found that under moderate saline irrigation (3 dS m^{-1}), tomato yield was not affected by the irrigation interval, while under highly saline irrigation (5 or 7 dS m^{-1}) the yield production was affected by irrigation intervals, leading to recommend the shortest irrigation interval.

Tedeschi and Menenti (2002) have concluded that alternating irrigation with fresh and saline water on soils that are already saline can mitigate the salinity, especially if fresh water is applied during the phenological stages most sensitive to salinity stress.

In some arid-saline lands such as the Northwest of China, soil mulching is already applied in combination with irrigation (Tedeschi, 2020). Ingman *et al*. (2015) point out the great amount of film used in this area of China and how the disposal of such material after use is not environmentally sustainable. The film is not recycled but burned or buried in the ground after use. Therefore is necessary to improve the application of mulching in this area together with irrigation, but the type of mulching should be eco-friendly, such as vegetable residues of previous crops: wheat, corn, or biodegradable plastics now available on the market. Zheng *et al*. (2002) demonstrated that wheat straw mulching effectively decreased soil surface evaporation and conserved soil water. Pang *et al*. (2010) applied six rates of wheat straw mulching combined with two irrigation water qualities, saline (5 dS m^{-1}) and freshwater (1.27 dS m^{-1}). The results showed a significant decrease in salt content in the upper 40 cm soil depth when straw mulching was implemented. For the deeper soil layer, instead, the results were less clear. Straw mulching seems to decrease the salt content on the surface of the soil by regulating the salt vertical distribution, which could reduce the salt damage to crops, enhance their yields and reduce the risk of soil salinization and erosion (Cuevas *et al.*, 2019).

Soil improvement

Saline water modifies soil's physical properties. Basile *et al*. (2011) document in detail the changes in soil physical properties under the application of saline irrigation water in soil with high clay content. In Huang *et al*. (2010) similar results were reported on silty loam soil. In both studies, soil affected by salinity underwent a reduction in total porosity with a loss of larger pores and an increase in smaller pores. Despite the difference in total porosity, the available soil water (ASW), calculated in the range of 100 cm and 10^4 cm pressure head for the layer of 100 cm depth, showed a similar trend at all examined sites (Tedeschi *et al.*, 2007, 2008a, 2008b). All irrigation and salinity treatments were applied to the same soil, but apparently, the saline treatments induced the partial occlusion of macropores, thus transferring part of the pore space to smaller pores. Water potential in macropores is close to zero and does not count in the estimation of ASW and of the total soil water retention capacity. The smaller pores in the soil under saline treatment accounted, therefore, for a larger fraction of ASW and of the total soil water retention capacity. This modification of the soil structure led to a shorter duration of soil water deficit, as illustrated in Tedeschi *et al*. (2007). Such findings are useful in planning and managing the irrigation of saline soils.

Saline soils are diverse in nature and require specific strategies, such as the application of sulfur-containing compounds to aid the management and reclamation for long-term productivity (Tomaz *et al.*, 2020; Bello *et al.*, 2021). Other related amendments such as sewage sludge, biochar, compost of municipal solid wastes, and zeolite have also been used to reclaim sodic soils (Bai *et al.*, 2017; Mukhopadhyay *et al.*, 2021).

Gypsum, when applied to saline soils, can improve the soil's physical and chemical characteristics and biomass and crop production (Bello *et al.*, 2021). Gypsum can be applied alone or in combination with other amendments such as manure, humic acid, biochar, and others. Ahmed *et al*. (2015) carried out a three-year field trial to assess improvement in soil physical and chemical properties of saline-sodic soil along with the production of fodder beet by using different remedial strategies. Their results showed that integrated application of farmyard manure (FM) and gypsum combined with chiseling can be highly beneficial in improving chemical and physical soil properties.

Similar results were obtained also from Shaaban *et al*. (2013) who conducted a field experiment to explore the effects of gypsum, FM, and commercial humic acid application on the amelioration of salt-affected (saline-sodic) soil. In their study, the application of gypsum with or without FM and commercial humic acid decreased soil pH, electrical conductivity (ECe), and sodium adsorption ratio (SAR) and increased the root length and yield of rice cultivated on such soil. Bayoumy *et al*. (2019) evaluated the effect of individual and combined applications of gypsum, compost tea, and biochar on some soil physical properties and wheat productivity under saline and saline-sodic soils. Results revealed that the combined amendments application decreased soil ECe and, SAR. Moreover, the application of different amendments decreased soil bulk density and increased soil porosity after two growing seasons.

Despite the positive feedback in the literature on the use of amendments to improvers/combat salinity, some constraints and problems relating to their availability and cost should be taken into account in order to evaluate the technical and economic feasibility of their use.

Mined gypsum is naturally available but the of poor quality and its availability to agriculture is limited due to its use within the cement industry. Moreover, gypsum must be well-mixed with the soil and followed by adequate water application to take out displaced Na$^+$ from the rhizosphere. Before planning the application of gypsum, it is useful to carry out a feasibility study to evaluate the costs of supplying gypsum in the quantities necessary to reduce salinity and assess the availability of good quality water. Mukhopadhyay *et al*. (2021) report that the application of municipal compost wastes combined with gypsum decreased soil salinity 120 days from application, despite it being initially increased. Caution is advised in the selection of municipal solid waste compost to avoid secondary pollution in treated soils. Biochar has become a popular amendment also for the reclamation of salt-affected soils. It should be stressed that the selection of biochar feedstock and pyrolysis temperature are important factors to be considered before applying this amendment to salt-affected soils. As reported by Sun *et al*. (2017), a high application rate of biochar can increase the loss of N by volatilization, with the well-known consequence of the rise of greenhouse gases. Fly ash is a combustion product of the coal industry that has a potential role in reclaiming sodic soil in combination with gypsum and green manure (Mishra *et al.*, 2019).

As a final remark about the use of amendments to improve soil quality by reducing the salinity of the soil, it should be underlined that amendments costs should be assessed and the availability of water of good quality should also be investigated.

Reducing the vulnerability of the crops to salt stress

Use of cultivars less sensitive to salinity

Crop rotation and the selection of salinity-tolerant species can improve the productivity of saline soils. Salt-sensitive plants are defined as glycophytes (Pan *et al.*, 2020), and can withstand only moderate salinity levels, with consequent reduction of crop production (Munns and Tester 2008). Salt-tolerant plants are defined as halophytes, and employ effective salt-tolerance mechanisms to avoid salt damage and survive salinity stress (Tester, 2003). Stress tolerance to salinity is a complex phenomenon, involving fine-tuned plant responses to osmotic and oxidative stress such as ionic homeostasis, membrane stabilization, and phytohormones production (Kumar *et al.*, 2021). Tolerant plants involve diverse regulatory mechanisms thanks to the reprogramming of the expression of several key genes, which is crucial to restore and re-establish cellular homeostasis during stress and the recovery phase (Kumar *et al*. 2021). Vita *et al*. (2021) compared the transcript profiling of two quinoa genotypes with contrasting salt tolerance, providing insights into the early-stage molecular mechanisms, both at the shoot and root level. Results showed the presence of varying differentially expressed genes among genotypes, tissues, and treatments, with genes related to hormonal and stress response upregulated, after short salt stress, mainly in the sensitive genotype. Basu and Roychoudhury (2021) compared four different genotypes of *indica* and *japonica* rice subjected to salinity stress, and found that the degree of the resistance was not related to the phylogenetic distance between the genotypes, but instead caused by subspecies-specific resistance mechanisms such as increased antioxidant potential and expression of genes involved in phenol biosynthesis. When studying sugar beet genotypes with varying tolerance to salinity, Naguib *et al*. (2021) report that the tolerant genotype increased the expression of genes involved in the raffinose biosynthesis and had higher raffinose levels in leaves, suggesting that it might act both as osmolyte and scavenger.

The study of the salt tolerance-associated mechanisms could be an effective strategy to improve and select NaCl-resistant crops, which can profitably grow in saline environments (Al Kharusi *et al.*, 2019; Bayuelo-Jimenez *et al.*, 2012). Carty *et al*. (1997) described saline soil reclamation by using halophytic vegetation and later, Ravindran *et al*. (2007) demonstrated that two halophyte species could accumulate greater amounts of salts in their tissues, thereby reducing soil salinity. These results suggest alternating years of saline reclamation by crops able to accumulate salts to years with glycophytes plants for food production. Bansal *et al*. (2021) studied the transcriptome of a halophyte rice variety grown at various NaCl levels, and report that the expression of genes encoding ABC and dicarboxylate transporters and DnaK and CML proteins and respiratory burst oxidase were specifically upregulated at high salinity level. The authors suggest that these genes could be used as markers for salt resistance or to engineer crops with increased salt tolerance. Tedeschi *et al*. (2017) found a higher tolerance of a cultivar when related to the concentration in the soil solution than the tolerance estimated according to the Mass and Hoffman relationship (M&H). The last result raises a question since the M&H relationship is based on salinity tolerances in conditions of soil water content at saturation. Under normal field conditions, soil water saturation may be attained occasionally and for a short time. Salinity tolerance relationships assessed on the basis of the concentration of irrigation water or to saturated soil may not be easy to apply and reference to saline concentration at the actual soil water content would be a practical guideline. If the salinity at the actual soil water content is considered, Tedeschi *et al*. (2017) found very different threshold values for melon crop. A threshold value of 2.71 dS m^{-1} was found when referring to the electrical conductivity of the saturated past (ECe), against a 3.99 dS m^{-1} when referring to the actual electrical conductivity of the soil solution (ECs). Also, the ECe and ECs at which a yield reduction of 50% (R 50%) of relative yield occurred, were 6.64 dS m^{-1} and 8.84 dSm^{-1}, respectively.

Manipulation of the rhizosphere

Plant-growth-promoting (PGP) microorganisms can alleviate salinity stress in plants by multiple mechanisms such as direct improvement of their nutritional status, production of PGP compounds, and decrease of stress-related metabolites (Oleńska *et al.*, 2020); furthermore, plant-associated microbes may behave as biocontrol agents against pathogens, which can be particularly deleterious to stressed plants (Atkinson and Urwin, 2012). Of particular interest for salinity tolerance are: i) synthesis of osmolytes to increase the cell osmotic pressure (Evelin *et al.*, 2013; Etesami and Beattie, 2018; Pollastri *et al.*, 2018); ii) production of enzymes to reduce the levels of reactive oxygen species and ethylene (Estrada *et al.*, 2013; Nascimento *et al.*, 2016; Acuña *et al.*, 2019); iii) bacterial excretion of exopolysaccharides which bind Na$^+$ and decrease its adsorption by plants (Etesami and Beattie, 2018); iv) regulation of Na$^+$ homeostasis (Garg and Baher, 2013; Bharti *et al.*, 2016); v) aquaporin synthesis by plants interacting with arbuscular mycorrhizal fungi (AMF), which can improve water uptake (Cheng *et al.*, 2021); vi) regulation of plant genes involved in salinity tolerance (Etesami and Beattie, 2018, Santander *et al.*, 2021).

Recently, Ma *et al*. (2022) studied the effect of the interaction with AMF on the physiology, ion flux, fatty acid (FA) metabolism, and transcriptome of jujube (*Ziziphus jujuba*) subjected to salt stress. The authors developed a model for FA metabolism rearrangements in AMF-colonized woody plants growing in high-salinity environments.

Moving to herbaceous plants, a study by Duc *et al*. (2021) investigated the physiology and biochemistry of the medicinal plant *Eclipta prostrata* grown at increasing NaCl levels and inoculated with various AMF, applied individually or in combination. The authors report that the mixture of multiple AMF was more beneficial than AMF applied singularly, affecting various traits such as proline and phenolic content, antioxidant enzymes activity, and increasing the yield.

Non-AMF fungi can also improve the growth of plants in saline environments. Endophytic fungi *Piriformospora indica* and *Tricoderma virens*, in combination with the foliar application of polyamine spermidine, have been reported to improve salinity stress tolerance of *Stevia rebaudiana*, leading to an increase in biomass, chlorophyll content, antioxidant enzymes' activity as well as a decrease in lipid peroxidation (Saravi *et al.*, 2022).

The soil as a reservoir of salt-stress-adapted microorganisms

In recent years, the importance of environments characterized by high salt levels as reservoirs of potential PGP microorganisms has been increasingly acknowledged, as such microorganisms are likely to have developed mechanisms to cope with salinity stress which can be beneficial for plants too (Ruppel *et al.*, 2013; Lumini *et al.*, 2020). Singh and Jha (2016) report that *Bacillus licheniformis* found in saline water increased wheat resistance to salt stress via increased soluble sugars content, improved ion balance, and auxin production. Maize plants subjected to high salinity had, among others, increased stomatal conductance, photosynthetic efficiency, and biomass when inoculated with AMF isolated from saline soil. Furthermore, one of the strains performed better than an analogous strain retrieved from a fungal collection, which was not adapted to saline environments (Estrada *et al.*, 2013). Similarly, when tomato plants subjected to salt stress were inoculated with three AMF, the one strain retrieved from a dry and saline environment was the most beneficial to plant adaptation, despite all AMF causing root metabolic reprogramming and enhancing plant growth (Rivero *et al.*, 2018).

Salinity can also shape the microbial community interacting with plants, selecting microorganisms that are beneficial against saline stress (Walitang *et al.*, 2018). For example, bacterial strains isolated from mangrove propagules displayed various PGP traits and increased the biomass of barley and rice subjected to high salinity (Soldan *et al.*, 2019). Klebsiella strains isolated from the rhizosphere of a desert native plant were able to synthesize various PGP compounds *in vitro* and, when inoculated on wheat subjected to salinity, increased the plant antioxidant activity and biomass (Acuña *et al.*, 2019). Also, AMF native to the rhizosphere of plants adapted to saline environments can be a valuable resource for increasing plant resistance to salt stress (Lumini *et al.*, 2020). Santander *et al*. (2021) report that the inoculation with AMF from the rhizosphere of a salinity-adapted shrub improved Na^+ root content, relative water content, and aquaporin expression of two lettuce varieties supplied with varying NaCl levels.

Soil microorganisms, particularly those which evolved in saline environments, represent an important but still largely unexpressed potential as enhancers of plant resistance to salt stress. Often products based on biostimulants struggle with providing benefits to crops when applied in the field, due to the competition with the local microbiota and environmental variability (Compant *et al.*, 2010). The effects of plant-microbe interactions can vary greatly among different species and environments (Hardoim *et al.*, 2015), hence general assumptions should be avoided and each potential PGP microorganism needs to be thoroughly tested in order to better comprehend and utilize the mechanisms underlying plant-microbe interactions.

Conclusions

The reviewed work highlights how agricultural soils are unstable and subject to changes in salinity level. Therefore, monitoring them is necessary at both the local and the regional scales. Newly available technologies can provide timely and reliable information to implement corrective actions to decrease salt concentration in the root zone, thus minimizing impacts on plant growth. The key to the success of any corrective intervention is detailed and accurate knowledge of soil properties to fine-tune soil and water management.

Combined with the above practices, the selection of crops tolerant to salinity should be considered, as well as the crop rotation of glycophytes for food production and halophytes for phytoremediation. Another beneficial factor of saline soils is the richness of AMF and PGPB in the rhizosphere, which can mitigate plant vulnerability to water and saline stress.

The described tools to contrast and mitigate salinity should be implemented one at a time or in combination. The uptake of innovations by farmers will depend on providing sufficient evidence on the economic and social benefits. Another challenge is that benefits of innovations in crops, irrigation management, and soil management typically appear on a longer timescale, thus making efforts in this directionless rewarding because the benefits are not immediately tangible.

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