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*Review paper*

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# Beyond salt stress: Unlocking the potential of sugar beet in saline environments

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**Abstract: Soil salinity is a growing constraint on crop production, especially in arid and semi-arid regions of the world where freshwater is scarce and irrigation water often has poor quality. Sugar beet (*Beta vulgaris* L.) is an important crop with relatively high salt tolerance that is increasingly valued for its potential to grow on marginal lands. This review combines current knowledge and recent advances in improving sugar beet's tolerance to salinity stress through agronomic practices, as well as physiological and environmentally friendly methods to manage salinity. Key topics include how sugar beet responds to salinity at the morphological and physiological levels, tolerance mechanisms such as osmotic adjustment and antioxidant activity, effects of salinity on yield and sugar quality, and various salinity mitigation strategies. These strategies involve the application of organic amendments (biochar, compost, humic substances), improved nutrient management (potassium, phosphorus, silicon, and micronutrients), biostimulants and plant hormones applied to the foliage (salicylic acid, melatonin, GABA), microbial inoculants (PGPR and AMF), and seed priming techniques. The review also discusses regulated deficit irrigation and the development of salt-tolerant cultivars. The importance of sustainable, low-impact approaches to enhance soil health, boost plant tolerance to stress, and improve water efficiency will be emphasized. Ultimately, this review identifies gaps in our understanding of sustainable interventions and offers guidance for future research to expand sugar beet cultivation in saline environments.**

## 1. Introduction

In semi-arid and arid regions, precipitation is often infrequent and

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irregular, access to freshwater is limited, and high temperature causes high rates of evapotranspiration (Ribeiro *et al*., 2024). Under such conditions, farmers rely on irrigation to prevent crops from experiencing drought stress and to maintain productivity (Gadelha *et al*., 2021). However, due to the scarcity of freshwater, low-quality or brackish water is often used for irrigation (El-Kady *et al*., 2021). Over time, this practice tends to increase soil salinity and degradation, ultimately reducing both the yield and economic value of the cultivated crops (Ahmed *et al*., 2007).

Soil salinity and sodicity pose a serious threat to food security by reducing crop productivity through mechanisms such as physiological drought, nutrient imbalances, and oxidative stress. Moreover, high concentrations of sodium ($Na^+$) and chloride ($Cl^-$) ions contribute to soil dispersion and can exert toxic effects on plant growth (Hafez *et al*., 2021; Othman *et al*., 2023). Therefore, adopting appropriate agricultural practices in arid regions is essential to enhance water use efficiency under drought and saline conditions (Pereira Filho *et al*., 2019). One promising strategy to address both freshwater scarcity and soil salinity, both of which are acute in semi-arid regions, is cultivating salt-tolerant crops such as sugar beet (*Beta vulgaris* L.) (Flowers, 2004). This crop offers additional benefits, including reducing dependency on imported sugar and providing valuable by-products for animal feed. It also has potential in renewable energy production through bioethanol and biomethane (Gumienna *et al*., 2016).

Sugar beet is a major industrial sugar crop, ranking second globally after sugarcane in production (Stevanato *et al*., 2001). The cultivation of sugar beet is expanding into marginal environments, particularly in arid and saline regions, due to its relatively high tolerance to soil salinity, with successful growth reported in soils with an electrical conductivity (EC) of up to 7.0 $dSm^{-1}$ (Lv *et al*., 2019). Sugar beet exhibits strong agronomic potential for arid and semi-arid regions due to its relatively low water and fertilizer requirements (Mekdad *et al*., 2021). For instance, studies have shown that the sugar beet crop consumes 30-40% less water than sugarcane (Carr and Knox, 2011), making it a more sustainable alternative in water-scarce environments. Its high water-use efficiency, coupled with relatively high salinity tolerance, underscores its suitability as a strategic industrial crop for marginal lands, especially those characterized by salt-affected soils and limited freshwater resources.

Nonetheless, elevated salinity in both soil and irrigation water can negatively impact root yield and sugar quality (Munns, 2002). As a result, sugar beet cultivation in semi-arid and arid regions faces dual challenges of low-quality irrigation water and degraded soils (Alharbi *et al*., 2022). Under such conditions, plant growth and metabolism are significantly disrupted, with the extent of damage depending on the type of stress, its duration, the developmental stage, and prevailing environmental conditions (Silva *et al*., 2022). For example, sugar beet is particularly sensitive to salinity during early growth stages, resulting in a reduced germination rate, seedling growth, and plant density, which ultimately lead to lower root and sugar yields (Ghoulam and Fares, 2001). However, during later growth stages, sugar beet can withstand high salinity levels without considerable yield loss. Cultural practices play a critical role in enhancing WUE and mitigating salt stress, particularly through the use of soil-tolerant varieties, adoption of appropriate irrigation techniques, and improvement of soil physical and chemical properties via organic acids and biostimulant treatments (Pereira Filho *et al*., 2019; El-Kady *et al*., 2021).

Countries relying on dryland farming can benefit from introducing sugar beet as a strategic, non-traditional crop. It would diversify agricultural systems, reduce dependence on water-intensive or imported crops, and improve resilience to climate variability by utilizing marginal saline soils and low-quality irrigation water. Additionally, sugar beet cultivation holds significant economic potential by creating employment opportunities on farms and in associated sugar processing facilities. It can also help reduce reliance on imported refined sugar, thereby decreasing national import expenditure. Moreover, utilizing sugar beet by-products, such as beet pulp for animal feed and molasses, adds circular economic value and promotes resource efficiency within the agro-industrial sector.

This review aims to assess the introduction of sugar beet as a salt-tolerant alternative crop in agricultural systems of semi-arid and arid regions, with the goal of enhancing resilience and sustainability. Current knowledge regarding agronomic, physiological, and environmental factors, as well as associated challenges, will be synthesized from comparable regions to identify key traits and agricultural practices needed for successful sugar beet cultivation under conditions such as salt-affected soils and low-quality irrigation water. By highlighting knowledge gaps, this review will provide information to support decision-making by researchers and policymakers on the integration of sugar beet into crop portfolios, aiming to improve crop diversification and sustainable agricultural practices under saline and arid conditions.

## 2. Botanical characteristics and salinity adaptation

Sugar beet (*Beta vulgaris* L.), a tuberous root crop belonging to the family Amaranthaceae, is native to the temperate regions of Europe and North Africa (Ribeiro *et al*., 2024). Within the cultivated beets, four primary groups are taxonomically identified: leaf beet, table beet, fodder beet, and sugar beet (Goldman and Janick, 2021). Sugar beet is primarily cultivated for sugar production, human consumption, and animal feed, and is globally recognized as the second most important sugar crop after sugarcane (*Saccharum officinarum* L.). Sugar derived from sugar beet accounts for approximately 30% of total global sugar production (Yolcu *et al*., 2021).

Compared to sugarcane, sugar beet is distinguished by a shorter growing season, lower water requirements, and a higher sugar content. For example, it has been reported that producing one kilogram of sugar from sugar beet requires approximately 1.4 $m^3$ of water, which is less than half the volume needed to produce the same amount of sugar from sugarcane (Brar *et al*., 2015). Sugar beet can be cultivated under a wide range of climatic conditions and is recognized for its tolerance to drought and salinity. It is believed to have evolved from sea beet (*Beta maritima* L.), a wild ancestor adapted to saline soils along the coasts of Western Europe and the Mediterranean regions (Rozema *et al*., 2015). Consequently, numerous sugar beet cultivars are regarded as salt-tolerant due to the inheritance of various physiological and morphological traits that enable them to withstand drought and salinity in both soil and irrigation water (Lv *et al*., 2019; Wang *et al*., 2024). For instance, it has been reported that sugar beet can tolerate high concentrations of sodium chloride (NaCl), up to 500 mM, for extended periods without loss of viability (Yang *et al*., 2012).

## 3. Effect of salinity on sugar beet

In general, soil salinity negatively impacts plant growth and development by altering various morphological and physiological characteristics, as well as disrupting biochemical processes at the cellular level (Abd El-Mageed *et al*., 2019). Salinity induces osmotic and oxidative stress, resulting in damage to cellular membranes and organelles (Ashrafi *et al*., 2018). Additionally, salinity is known to impair the synthesis of proteins and metabolic enzymes, thereby reducing the rate of photosynthesis. When salinity is combined with drought, as commonly occurs in arid and semi-arid regions, the resulting impact on plant growth can be particularly detrimental.

Sugar beet is classified as a salt-tolerant glycophytic species, exhibiting optimal growth under low concentrations of sodium ($Na^+$), which can partially substitute for potassium ($K^+$) in specific non-specific metabolic processes (Wakeel *et al*., 2011). The optimal growth of sugar beet has been reported to occur under 10% seawater salinity; however, exposure to 25% seawater salinity resulted in a significant reduction in fresh biomass compared to plants grown under 10% salinity (Daoud *et al*., 2008). Under low-salinity conditions, sugar beet exhibits enhanced growth performance, characterized by efficient water and nutrient uptake, stimulated root development, and improved physiological responses to salt stress (Liu *et al*., 2008; Wang *et al*., 2024). These traits indicate that sugar beets can be successfully cultivated under mild saline, alkaline, and drought conditions; however, it is essential to note that salinity levels exceeding specific thresholds can lead to growth inhibition due to salt-induced damage at the morphological, cellular, and molecular levels (Wang *et al*., 2024).

At the morphological level, sugar beet plants exposed to saline stress exhibit reduced seed germination and seedling growth, a decrease in leaf number and surface area, as well as leaf deformation and discoloration. Additionally, overall root development is adversely affected, particularly in terms of root length and lateral root formation (Wang *et al*., 2017). At the cellular level, the detrimental effects of salinity on sugar beet plants encompass osmotic, oxidative, and ionic (toxic) stress (Mulet *et al*., 2020). Osmotic stress arises from elevated external salinity, which restricts water uptake and can lead to dehydration by drawing water out of the cells. Consequently, osmotic stress is primarily manifested by cellular dehydration, disintegration of membrane structures, and disruption of metabolic processes (Rasouli *et al.*, 2020).

On the other hand, oxidative stress results from the excessive accumulation of reactive oxygen species (ROS), which are harmful to various cellular components, including proteins and nucleic acids such as DNA (Zhao *et al.*, 2020). Moreover, toxic stress results from elevated concentrations of $Na^+$ and $Cl^-$ ions, leading to nutrient imbalances that hinder the uptake of essential minerals such as $K^+$, $Ca^{2+}$, and $Mn^{2+}$, and disrupt cellular osmoregulation (Yolcu *et al.*, 2021). However, increasing the salinity of irrigation water corresponds with an increased concentration of soluble Ca, Mg, and Na, whereas K exhibits decreased solubility (El-Kady *et al.*, 2021). At the molecular level, sugar beet responses to salinity include modifications to gene expression, protein synthesis, stress response mechanisms, and other metabolic pathways (Yu *et al.*, 2016). For instance, ABA signaling is impacted under salt stress through the expression of specific transcription factors (Wang *et al.*, 2024). Additionally, the functions of specific stress proteins in sugar beet (such as 14-3-3 proteins) are also modified, for example, through induced protein phosphorylation, helping to mitigate the effect of salinity by enhancing ROS detoxification and cell wall synthesis (Sheikh *et al.*, 2024).

Salinity also tends to disrupt photosynthesis in sugar beet by inducing stomatal closure, limiting $CO_2$ uptake, and impairing photosynthesis efficiency (Skorupa *et al.*, 2019). Furthermore, ionic imbalances, particularly $K^+$ deficiency and $Na^+$ accumulation, damage photopigments, chlorophyll content, and certain enzymes, resulting in lower photosynthetic rates (Yolcu *et al.*, 2021). These effects highlight the complex responses of sugar beet to salt stress and collectively contribute to its adaptive tolerance to salinity. Figure 1 provides an overview of the multilevel impact of salinity on sugar beet, as well as the adaptive mechanisms under mild salt stress.

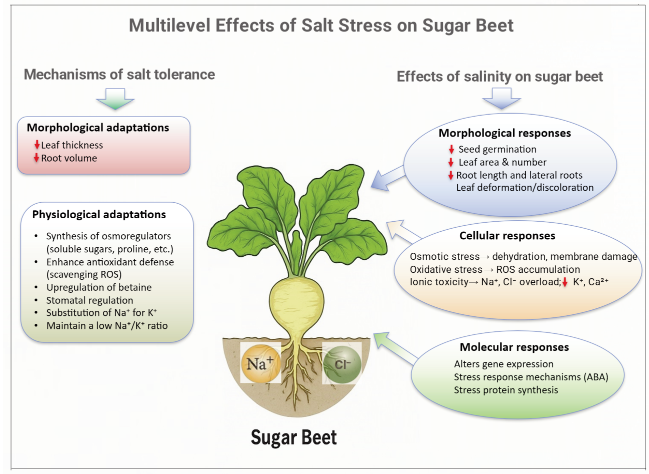


Fig. 1 - Multilevel effects of salinity stress on sugar beet growth and physiology. The diagram illustrates the morphological, cellular, molecular, and physiological disruptions caused by salt stress. Under mild salinity conditions, sugar beet exhibits adaptive traits, including enhanced root growth, efficient water and nutrient uptake, partial substitution of $Na^+$ for $K^+$ in metabolic processes, and activation of antioxidant defense systems. These responses contribute to the species' relatively high tolerance and potential for cultivation in saline environments.

## 4. Mechanisms of salt tolerance in sugar beet

Sugar beet displays a range of morphological and physiological adaptations to salinity stress, including reduced root volume, increased leaf thickness, and regulation of stomatal opening to minimize transpiration losses (Van Zelm *et al.*, 2020). Physiological adaptations include the synthesis of osmoregulatory compounds - such as proline, soluble sugars, and organic acids - to maintain cellular osmotic balance, as well as the enhancement of antioxidant defense systems to mitigate oxidative stress by scavenging ROS and preventing cellular damage (Zhang *et al.*, 2021). An experiment investigating the effects of varying seawater concentrations on sugar beet growth demonstrated that osmotic adjustment, achieved through the accumulation of intracellular solutes, constitutes a primary mechanism underlying sugar beet's tolerance to salinity (Daoud *et al.*, 2008).

In addition to the aforementioned mechanisms, salt tolerance in sugar beet also involves the upregulation of betaine synthesis and accumulation, which contributes to the protection of photosynthetic enzyme activity and alleviation of osmotic stress by regulating intracellular water potential (Russell *et al.*, 1998). Furthermore, under potassium-deficient conditions resulting from nutrient imbalance, sugar beet has been shown to partially substitute $Na^+$ for $K^+$ in key physiological processes, such as stomatal regulation, enzyme activation, osmoregulation, and long-distance transport, thereby supporting continued growth under salt stress (Faust and Schubert, 2017). The relatively higher salt tolerance observed in specific sugar beet cultivars has been attributed to their capacity to maintain a low $Na^+/K^+$ ratio and to accumulate greater concentrations of compatible solutes (Wu *et al.*, 2019). Sugar beet also possesses the ability to compartmentalize and sequester salt ions ($Na^+$ and $Cl^-$) in petioles and older leaves, thereby mitigating their toxic effects on metabolically active, functional leaves (Wang *et al.*, 2012).

## 5. Salt stress mitigation strategies for sugar beet cultivation

Soil salinity is a major abiotic stress that constrains crop cultivation by adversely affecting plant growth and yield. Its multifaceted impacts include impaired water and nutrient uptake, toxicity from excessive sodium and chloride ions, and increased oxidative damage resulting from elevated levels of ROS (Abu-Ellail and Sasy, 2021; Mosaad *et al.*, 2022; El-Atrony *et al.*, 2025 a).

The potential for expanding sugar beet cultivation into saline-affected regions is supported by its relatively high tolerance to salt stress, as previously demonstrated in the preceding sections. However, when salinity levels exceed a critical threshold, even relatively high salt-tolerant glycophytic crops, such as sugar beet, exhibit substantial reductions in growth, root biomass, and sugar yield. Consequently, the development and implementation of effective salt stress mitigation strategies are essential for sustaining successful sugar beet cultivation in saline soils, particularly in arid and semi-arid regions. The following sections will present a range of ameliorative strategies, derived from recent research, examining their impact on sugar beet growth and development under saline conditions, as well as their effectiveness in mitigating the detrimental effects of salinity. Figure 2 presents an overview of the primary strategies employed to mitigate salt stress in sugar beets.

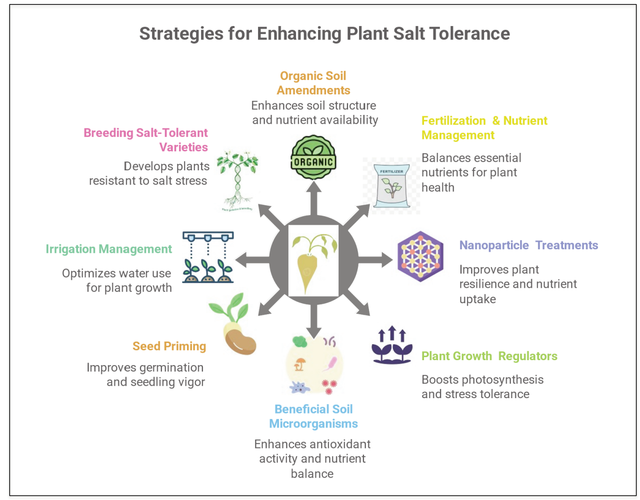


Fig. 2 - Overview of mitigation strategies for improving salt stress tolerance in sugar beet. The visual summarizes eight major approaches: (1) application of organic amendments such as biochar, compost, and humic substances; (2) nutrient management including potassium, micronutrients, silicon, and phosphorus; (3) foliar and seed treatment with nanoparticles; (4) use of plant growth regulators and biostimulants; (5) inoculation with beneficial soil microorganisms such as PGPR and AMF; (6) seed priming techniques; (7) optimized irrigation management through deficit irrigation; and (8) breeding of salt-tolerant varieties. These strategies enhance physiological, biochemical, and agronomic traits to improve sugar beet performance under saline conditions.

## 6. Organic amendments

As shown in Table 1, soil amendments with various types of organic materials have demonstrated significant potential to enhance the growth and yield of sugar beet under cultivated saline conditions. The following sections provide a detailed discussion of the impact of organic amendments in mitigating salt stress in sugar beet.

*Biochar*

Soil amendments using organic materials - particularly compost, biochar, and humic substances - have recently garnered considerable attention as eco-friendly strategies for sustaining soil quality through the improvement of physicochemical properties (Tomczyk *et al.*, 2020; Su *et al.*, 2022; Abdou *et al.*, 2023; Abdou *et al.*, 2024). These amendments increase soil carbon content, which enhances nutrient exchange capacity, stimulates microbial activity, promotes balanced nutrient uptake, and supports overall plant growth (Ghorbani *et al.*, 2022). Consequently, the application of organic matter improves key soil functional properties,

Table 1 - Organic amendments for salt stress mitigation

| Organic amendment | Salinity level (EC $dSm^{-1}$) | Rate/(Additives) | Mechanism of action/benefits | Key findings/impact on Sugar Beet under salinity | References |
|---|---|---|---|---|---|
| Biochar | 10.3 | 10-20 (t/ha) | Improved water productivity as well as soil physical and chemical properties | 20 t/ha biochar gave the highest root and sugar yields | Abdou *et al.*, 2024 |
| Biochar | 10.94 | 0/10/20 (t $ha^{-1}$) | 20 t $ha^{-1}$ reduced bulk density (-2.9%) and soil EC (-12.5%). Enhanced water availability and CEC | Improved growth, yield, quality and physiological attributes | El-Samnoudi *et al.*, 2021 |
| Compost + Glauconite | 4.3 | Compost (0-150% of recommendation)/ + (Glauconite at 0-190 kg/ha) | Reduces soil EC[1] and ESP[2]; increases soil nutrients | Increase sugar beet root yield, sugar yield and quality | Shabana *et al.*, 2024 |
| Molasses (M) + Humic acid (HA) | 7.9-8.8 | HA (12 kg/ha), M (60 kg/ ha) + foliar application of Ha and M/ + (Lithovit/Boron) | Increased growth parameters (leaf area index, dry weight, root weight, length, diameter) | Combined soil and foliar application of Ha, M, and Lithovit/Boron produced the highest root and sugar yield | Sorour *et al.*, 2021 |
| Humic acid (HA) | 45-4.6 | Humic acid (0-24 kg/ha) + foliar salicylic acid, fulvic acid, hydroxyproline | Enhancing growth characteristics and helping mitigate soil salinity | HA achieved the highest growth at 24 kg/ha to the soil, combined with foliar spraying of Fulvic acid and Hydroxyproline | Nassar *et al.*, 2023 |
| Humic substances | 9.7-11.3 | Soil humic/fulvic acids + Bacillus biofertilizer | Increased proline level and nutrient uptake; reductions in soil EC and ESP | Higher root yield and quality | El-Atrony *et al.*, 2025 a |
| Novel compost (NC) | 6.4-7.1 | bagasse + animal blood. NC with 70:30 ratio (bagasse:blood) at 10–20 t/ha) | Improved soil properties and water productivity; reduced the uptake of Cd | The highest yields (root yield 97.2 t/ha) were observed under full irrigation with 20 t/ha NC | Abd El-Mageed *et al.*, 2019 |
| Compost tea (CT) | 11.1-12.1 | Foliar compost extract + soil PSB[3] | Enhance physiological functions; boost antioxidants and osmolytes; enhance nutrient (P) availability | PSB and CT have beneficial effects on growth and quality of sugar beet growing in salt-affected soil. | Osman *et al.*, 2022 |
| Moringa leaf extract (MLE) | 0-120 mM NaCl[4] | Seed priming (soaking) in MLE at 100-300 ml/L + Algae and yeast extracts | Improves seedling parameters (root and shoot lengths, seedling length, and seedling vigor index) | 300 mL/L moringa extract yielded the highest seedling growth under salinity | Kandil *et al.*, 2023 |
| Compost (manure) | 6.0-6.2 | Soil compost (0.8-2.4 ton/ha) | Influence various growth, yield, and quality parameters (e.g., increasing root diameter, fresh weight, sucrose, and decreasing alpha-amino N) | 2.4 ton/ha compost increased root diameter, fresh weight and sugar yield | Abu-Ellail and Sasy, 2021 |
| Humic substances + Nitrogen fertilization | 8.63 | Soil humic/fulvic acid (30 kg/ha) + N (71–213 kg/ha) | Increases nutrient uptake and sugar synthesis; reduces Na content | Humic substances (30 kg/ha) and 213 kg N/ha + gave the highest root and sugar yields | Mosaad *et al.*, 2022 |

EC= Electrical conductivity; ESP= Exchangeable sodium percentage; PSB= Phosphate-solubilizing bacteria.

particularly those linked to enhancing crop resilience to abiotic stresses such as salinity (Abd El-Mageed *et al*., 2019; El-Samnoudi *et al*., 2021; Osman *et al*., 2022).

Among organic amendments, biochar has attracted particular interest due to its capacity to enrich soil with a high content of stable carbon, which, unlike other organic materials such as compost, remains persistent in the soil over the long term (Haider *et al*., 2020). Biochar is produced through thermal decomposition of biomass, typically under limited or no oxygen conditions, via processes such as pyrolysis or hydrothermal carbonization (Saravanan and Kumar, 2022). These processes break down biopolymers, yielding structurally stable carbon-rich materials. In addition to increasing soil carbon content, biochar enhances soil water retention, reduces bulk density, improves nutrient retention by increasing cation exchange capacity (CEC), and stimulates microbial activity (Alkharabsheh *et al*., 2021; Singh *et al*., 2022). Soil amendment with biochar has been proposed as a promising strategy to enhance sugar beet resilience to abiotic stresses, particularly salinity and drought. For instance, the application of biochar has been shown to mitigate the adverse effects of salinity and drought on sugar beet by enhancing physiological and biochemical processes under stress conditions (Abdou *et al*., 2024).

In sugar beet field studies, biochar has been applied at 10-20 t $ha^{-1}$ across two successive seasons under saline conditions (ECe ≈ 10-11 dS $m^{-1}$) and deficit irrigation (≈ 60-80% ETc), with the 20 t $ha^{-1}$ rate improving soil physical status (e.g., lower bulk density and ECe; higher field capacity and available water), growth, and water productivity (El-Samnoudi *et al*., 2021; Abdou *et al*., 2024). Complementary long-term evidence from highly saline-alkali paddy soils shows that a one-off biochar application sustained annual improvements in soil physical and chemical properties and increased rice yield over six years (Jin *et al*., 2024). The benefits were most significant at 3.0% (w/w) and were enhanced when combined with nitrogen fertilizer. In contrast to the consistent yield responses, data on sugar composition and juice-quality parameters (e.g., sucrose %, purity, α-amino N, K/Na) were insufficient across the present field investigations, underscoring the need for targeted studies to quantify biochar's effects on sugar quality under salinity. Further details are provided in Table 1.

*Compost*

The application of various types of compost as soil amendments has also been investigated for its effectiveness in improving sugar beet cultivation under saline conditions (Abu-Ellail and Sasy, 2021; El-Atrony *et al*., 2025 a). For instance, the application of a novel compost composed of sugarcane bagasse and animal blood in a 70:30 (w/w) ratio at a rate of 20 t/ha effectively mitigated the adverse effects of salinity and drought on sugar beet cultivation, resulting in approximately a 50% increase in root yield compared to the control treatment (Abd El-Mageed *et al*., 2019). In that study, soil EC was 6.89 dS $m^{-1}$; applying 20 t/ha increased white sugar yield and juice purity by 65.5% and 3.23%, respectively, and reduced α-amino N and sugar loss to molasses by 11% and 12.20% relative to the control. The application of tea compost in combination with phosphate-solubilizing bacteria has also been reported to enhance sugar beet performance under salinity and drought stress by improving osmotic balance, photosynthetic efficiency, and root development (Osman *et al*., 2022). In these salt-affected trials, soil and irrigation-water ECs were 11.14 and 1.37 dS $m^{-1}$, respectively; improvements in sugar quality were associated with decreased impurity constituents (α-amino N, Na, K) and higher juice purity under water stress. Similarly, a mixture of compost and glauconite (a mineral rich in potassium) significantly improved soil physical properties such as bulk density and porosity, increased the availability of macro- and micronutrients, and enhanced both sugar yield and quality in sugar beet grown under saline and sodic conditions (Shabana *et al*., 2024). At that site (EC = 3.41 dS $m^{-1}$), the combination reduced EC, improved organic matter and soil physical status, increased N, K, Fe, Mn, Zn, and Cu, and enhanced sugar quality with minimal sugar loss to molasses (~2.43%) alongside reductions in K, Na, and α-amino N. Further details are provided in Table 1.

*Humic substances*

The application of humic substances has also demonstrated promising potential in enhancing sugar beet resilience to salinity stress. Several field studies have reported that the application of humic acid, fulvic acid, and related organic materials significantly enhances the growth, yield, and physiological performance of sugar beet under saline conditions. For instance, Sorour *et al*. (2021) reported that the combined application of humic acid and molasses, applied through both soil and foliar treatments, significantly improved the growth parameters of sugar beet cultivated under saline conditions (soil EC ≈ 8.8 dS $m^{-1}$; irrigation-water EC ≈ 2.01 dS $m^{-1}$) (Sorour *et al*., 2021). Similarly, under saline-sodic conditions (soil EC ~11.3 dS/m and exchangeable sodium percentage (ESP) >15%), the application of a mixture of organic substances - including humic acid, fulvic acid, and potassium humate - in combination with a Bacillus-based biofertilizer, enhanced sugar beet productivity and nutrient uptake, while also mitigating the impact of soil salinity through significant reductions in both EC and ESP (El-Atrony *et al*., 2025 a). Furthermore, another study demonstrated that the application of humic and fulvic acids, in conjunction with high nitrogen fertilization, resulted in a more than 15% increase in both root yield and sugar extraction percentage in sugar beets cultivated under saline conditions (soil EC ≈ 8.63 dS $m^{-1}$; irrigation-water EC ≈ 3.2 dS $m^{-1}$) (Mosaad *et al*., 2022).

Soil-applied humic substances act through the rhizosphere and soil matrix, improving aggregation and water storage, enhancing nutrient availability/CEC, and moderating salinity (e.g., reductions in EC/ESP), which together support higher growth and extracted sugar under saline conditions (Mosaad *et al*., 2022; Abdel-Salam *et al*., 2025; El-Atrony *et al.*, 2025 a). In contrast, foliar applications of humic/fulvic compounds primarily exert physiological effects, raising chlorophyll and canopy vigor, improving membrane stability and photosynthetic efficiency, and can contribute to improved juice-quality indices under stress, particularly when integrated with soil applications (Sorour *et al*., 2021). In practice, combined soil and foliar applications can outperform single-route applications under salinity by simultaneously improving soil-plant conditions and canopy physiology (Sorour *et al.*, 2021; Mosaad *et al*., 2022; El-Atrony *et al*., 2025 a). These studies provide evidence that soil organic amendments, including compost and humic substances, represent effective strategies for mitigating salinity-induced stress in sugar beet cultivation. Further details are provided in Table 1.

## 7. Fertilization and nutrient management

Worldwide, arable lands are increasingly subjected to salinization due to soil and irrigation water salinity. One ameliorative measure to help crops withstand the adverse effects of salinity is optimizing fertilization practices. Recent studies have investigated various fertilization management strategies to mitigate the impact of salinity on the growth and productivity of sugar beet (Table 2).

*Potassium*

Exploring the role of potassium and micronutrient fertilization in alleviating the adverse effects of salinity on sugar beet has received considerable attention. Under salinity conditions, potassium is essential for maintaining osmotic balance and supporting membrane function. It has been found that foliar application of potassium silicate ($K_2SiO_3$, 20 mmol $L^{-1}$) significantly alleviates salt stress (EC ≈ 7 dS $m^{-1}$) by enhancing water productivity, chlorophyll content, and root yield under combined drought and salinity conditions (Shaaban *et al*., 2025). In another study, it has been reported that a combined treatment of potassium at a rate of 180 kg/ha and foliar application of Zn at a rate of 300 ppm resulted in a substantial improvement in root and sugar yield, up to 23% and 38%, respectively (EC ≈ 8.6 dS $m^{-1}$) (Mekdad *et al*., 2021). Physiological traits such as membrane stability, antioxidant activity, and relative water content of salt-stressed sugar beet were improved by high potassium application (144 kg/ha), alongside a 42% reduction in sodium and a 35% increase in root yield (EC ≈ 3.5-9.3 dS $m^{-1}$) (El-Mageed *et al*., 2022).

Moreover, synergistic effects between potassium fertilization and foliar application of salicylic acid were also observed in sugar beet. For example, it has been found that potassium fertilization at a rate of 200 kg/ha, combined with foliar application of salicylic acid, improved sugar content by 20% (Nemeat Alla, 2023). Meanwhile, a combination of 115 kg $K_2SO_4$/ha with salicylic acid significantly increased root yield and sugar quality under salinity conditions (EC ≈ 6.9 dS $m^{-1}$). These integrated fertilization strategies can be used practically to enhance sugar beet tolerance to salinity through improving physiological and biochemical responses. Further details are provided in Table 2.

*Micronutrients*

Micronutrients such as iron, manganese, zinc, and selenium play a crucial role in osmoprotection and the regulation of stress enzymes. Foliar application of Fe (150 ppm), Zn (100 ppm), and Mn (50 ppm) increased root and sugar yield, as well as quality index under saline conditions (EC ≈ 9.3-9.5 dS $m^{-1}$) (Abd El-Mageed *et al*., 2021). In this experiment, higher sugar and root yields of salt-stressed sugar beet were attributed to improved nutrient uptake, leaf hydration, and photosynthetic efficiency. Moreover, seed priming of sugar beet with selenium ($Na_2SeO_3$) at concentrations of 20 µM and 30 µM enhanced germination and seedling vigor, increased photosynthesis, and increased the activity of antioxidant enzymes under 300 mM $Na^+$ salinity (Liu *et al*., 2025). These results were primarily attributed to the modification of the rhizosphere microbial community. In the absence of imposed salinity, under an alkaline soil environment, foliar application of zinc (100 mg $L^{-1}$) and molybdenum (40 mg $L^{-1}$) increased sugar percentage, sugar purity, and growth parameters by improving balanced nutrient uptake and translocation (Zewail *et al*., 2020). Further details are provided in Table 2.

*Silicon*

Silicon applications have demonstrated beneficial effects on sugar beet performance by improving ion

Table 2 - Nutrient management for salt stress mitigation

| Nutrient/Strategy | Salinity level ($dSm^{-1}$) | Application method/rate | Mechanism of Action/Benefits | Key Findings/Impact on Sugar Beet under Salinity | References |
|---|---|---|---|---|---|
| Foliar micronutrient mix (Fe, Zn, Mn) | 9.3-9.5 | Foliar spray 0-150 ppm $FeSO_4^+$ 0-100 $ZnSO_4^+$ 0-50 $MnSO_4$ | Supplies essential micronutrients to support chlorophyll formation, enzyme activity, and osmotic balance; raises K/Na ratio | A 150-300 ppm mix significantly boosted growth, water status, and yield; 300 ppm increased root yield by 42% and sugar yield by 93% compared to the control | Abd El-Mageed *et al.*, 2021 |
| Soil K fertilizer | 3.5-9.3 | Soil K at 0, 48, 96, 144 kg K $ha^{-1}$ | Improves osmotic/ionic balance; enhances antioxidant capacity and photosynthetic performance | K = 144 kg $ha^{-1}$ maximized gross and white sugar; Na ↓ 42%, root yield ↑ 35.9% | El-Mageed *et al.*, 2022 |
| Foliar silicon (various forms) | --- | Foliar spray of potassium silicate (PS), calcium silicate (CS), sodium metasilicate (SM), orthosilicic acid (OSA) | Enhance photosynthesis and stress signaling; affect sugar technological quality; reduce sodium content in roots | PS and OSA sprays increased sugar yield; OSA most reduced root Na and i ncreased sugar content; spray form/ timing influenced sugar and K content | Siuda *et al.*, 2023 |
| Soil K fertilizer + Salicylic acid (SA) | 7.6 | Soil $K_2SO_4$ at 0, 100, 150, 200 kg/ha + two foliar SA sprays (1000 mg/L each) | Enhances root length and diameter, shoot and root yield, sucrose content, juice purity, sugar yield, -and uptake of N, P, and K | 200 kg K/ha + SA gave the highest root/sugar yields, sucrose% and purity | Merwad, 2016 |
| Soil K + Foliar Zn | 8.6 | Soil K at 120 or 180 kg/ha + foliar Zn at 0, 150, 300 ppm | Correct K and Zn deficiencies in saline soil; improve sugar beet growth, yield, quality, and K-use efficiency | K-180 + Zn-300 produced ~23% higher root yield and 38% higher pure sugar vs control; reduced impurities (Na/α-amino N) | Mekdad *et al.*, 2021 |
| K-fertilizer + SA | 6.9 | Soil $K_2SO_4$ 10 or 20 kg/ha and foliar K + SA foliar spray at 100,150, or 200 ppm | K increases growth parameters yield components; SA improves growth, yield, and sugar quality | 48 kg K + 2 foliar K + 200 ppm SA gave the highest root diameter, yields, and quality | Nemeat Alla, 2023 |
| Phosphorus | 12 | Soil $P_2O_5$ at 100, 120, 140 kg/ha | P enhances sugar beet's tolerance to salinity and improves both yield and sugar content | 120 kg $P_2O_5$/ha was optimal, improving root and sugar yields under saline irrigation; higher P increased sugar content at moderate salinity | Bouras *et al.*, 2021 |
| Soil K × P interaction | 5.0-9.0 | $K_2SO_4$ at 0, 75, 150 kg $K_2O$ $ha^{-1}$ × DAP at 0, 60, 120 kg $P_2O_5$ $ha^{-1}$ | K lowers leaf Na and Na:K ratio; P improves P nutrition | Fresh beet yield ↑ 15-84% across K×P vs control; shoot yield gains; strong leaf K/yield positive relationship | Hussain *et al.*, 2014 |
| Foliar Zn, B, Mo | -- | Foliar Zn (50 and100 mg/L), B (50 and 100 mg/L), Mo (20 and 40 mg/L) | Balancing nutrient uptake and translocation. Increased growth parameters (root diameter, length, fresh/dry weight), and improved nutrient contents (N, P, K, C | Zn 100 mg/L and Mo 40 mg/L gave the highest root yield and sugar%; all micronutrient sprays increased growth and leaf nutrient (NPK, Ca, Mg) content | Zewail *et al.*, 2020 |
| Selenium (Se) seed priming ($Na_2SeO_3$) | 300 mM $Na^+$ | Seed priming at 20 and 30 µM $Na_2SeO_3$; salinity during germination and pot stages | Enhances antioxidant enzymes, photosynthetic pigments, and ion balance; modulates rhizosphere microbiome | Se-priming improved germination and seedling vigor, ↑ soluble sugars/ proteins, ↓ MDA, and optimized microbial community | Liu *et al.*, 2025 |
| Foliar potassium silicate ($K_2SiO_3$) | 7 | Foliar $K_2SiO_3$ at 0, 10, 20 mmol/L under three deficit irrigation regimes | Improves physiological and biochemical traits, photosynthetic efficiency, osmolyte accumulation, antioxidant activity, and nutrient uptake | $K_2SiO_3$ (20 mmol/L) resulted in the highest root yield (88.97 t/ha) and sugar yield (14.43 t/ha) | Shaaban *et al.*, 2025 |
| Soil K-humate + foliar biostimu-lants (SA, fulvic acid (FA), hydroxy-proline (HP) | 4.7 | Soil K-humate at 0, 12, 24 K-muhate at 0 -24 kg/ha + foliar (SA 100 mg/L, FA 1.2 kg/ha, HP 1000 mg/L) | Enhanced growth traits, higher yields, increased sucrose, and reduced sodium content in the juice | 24 kg/ha K-humate + foliar FA+HP gave highest growth, root and sugar yields and lowest juice Na under salinity | Nassar *et al.*, 2023 |

balance and physiological functioning. Under combined salinity and drought, foliar potassium silicate at 20 mM significantly enhanced physiological responses, increasing sugar yield and water-use efficiency (EC ≈ 7 dS $m^{-1}$) (Shaaban *et al.*, 2025). Complementarily, in a study without imposed salinity, foliar potassium silicate and orthosilicic acid (at 49 g $ha^{-1}$ and 3 g $ha^{-1}$, respectively) enhanced the quality of sugar beet yields by reducing Na and α-amino nitrogen levels while increasing sugar content (Siuda *et al*., 2023). Further details are provided in Table 2.

*Phosphorus*

Phosphorus application has also been found to counter salinity-induced yield reduction in sugar beet. The application of phosphorus at a rate of 120 P2O5/ha enhanced the salt stress resilience of sugar beet, as it significantly improved sugar yield under salinity levels of up to 12 dS/m (Bouras *et al.*, 2021). Similar results were also observed for a combined application of potassium and phosphorus in saline and sodic soils (EC = 5.0-9.0), where both nutrients improved ionic balance and the yield of sugar beets, particularly by enhancing the Na: K ratio (Hussain *et al*., 2014). Further details are provided in Table 2.

## 8. Nanoparticle treatments

Recently, the application of nanoparticles (NPs) in agriculture has emerged as a promising and sustainable strategy to help crops mitigate the adverse effects of abiotic stress, improve nutrient balance, and improve growth parameters. NPs are characterized by nanoscale size, enhanced penetration, and high reactivity with plant cell components (Singh *et al*., 2024). Therefore, NPs can offer practical and novel approaches to alleviate the adverse effects of salt stress on sugar beet mainly by enhancing antioxidant activities, nutrient uptake, and helping plants to maintain ionic balance. For instance, sugar beet grown in saline soil (EC=6.8) and irrigated with saline water (EC = 5.7) and cultivated in saline soils exhibited improved growth and yield parameters, along with reduced salt-induced oxidative stress, when treated with a foliar application of silica nanoparticles ($SiO_2$-NPs; 12.5 mg $L^{-1}$) in combination with rhizobacteria (Alharbi *et al*., 2022).

In another experiment, seed priming and foliar application of nanoparticles composed of magnesium oxide (MgO-NPs at 50 mg $L^{-1}$) and silicon oxide ($SiO_2$-NPs at 50 mg $L^{-1}$) improved the growth and yield of sugar beet irrigated with wastewater (EC = 1.61) by increasing chlorophyll content and sucrose accumulation in leaves, as well as enhancing the activity of antioxidant enzymes (Ali *et al*., 2025). Moreover, foliar application and seed priming with titanium dioxide nanoparticles ($TiO_2$-NPs) at a rate of 100 ppm priming and 200 ppm spray combined with silver nanoparticles ($AgNO_3$-NPs) at a rate of 30 ppm priming +75ppm spray in sugar beet cultivated under saline soil conditions (EC = 4.2) significantly enhanced sugar content and extraction efficiency, while concurrently reducing sugar impurities compared to untreated controls (Gomaa *et al*., 2022). Further details are provided in Table 3.

## 9. Plant endogenous metabolites

Among hormones, indole-3-acetic acid (IAA) plays a role in enhancing plant resilience to abiotic stress. Under salinity (EC ≈ 7 dS $m^{-1}$), exogenous IAA - particularly 300 mg $L^{-1}$ combined with 340 kg N $ha^{-1}$ - enhanced root growth and nutrient uptake (higher $K^+/Na^+$, $Ca^{2+}/Na^+$), increasing root (97.6 t $ha^{-1}$) and pure sugar (14.50 t $ha^{-1}$) yields (Shaaban *et al*., 2025). In another experiment, the use of growth-promoting rhizobacteria has been shown to enhance the performance of sugar beet under salinity conditions (Alharbi *et al*., 2022); in salt-affected soil (EC 6.8) with saline irrigation (EC 5.7), seed inoculation with PGPR (*Pseudomonas koreensis*, *Bacillus coagulans*) at 150 mL of $1 \times 10^8$ CFU $mL^{-1}$, enhanced antioxidant defenses (SOD up to ~1.9-fold, CAT ~1.4-fold, POX ~2.5-fold), reduced $H_2O_2$, lipid peroxidation, and $Na^+$, increased $K^+$, and improved RWC, RMSI, stomatal conductance, chlorophyll, and ultimately root and sugar yields across two seasons. In general, rhizobacteria such as *Bacillus* and *Pseudomonas* enhance plant tolerance by the biosynthesis of PGRs such as IAA, gibberellins, and cytokinins, in addition to the production of exopolysaccharides that can chelate sodium ions in the soil and reduce their influx (Yang *et al*., 2016).

Also the use of plant hormone-like substances, such as salicylic acid (SA), have been widely utilized in sustainable agriculture to mitigate the effects of adverse abiotic factors (Rašovský *et al*., 2022). For instance, under saline condition (EC 7.5 ), the salt tolerance of sugar beet was improved by foliar application of SA (at the rate of 200 ppm), which enhanced the activities of antioxidant enzymes, resulting in higher root biomass and sugar yield (El-Gamal *et al*., 2021). The beneficial effect of SA in alleviating abiotic stress has been attributed to the

Table 3 - Nanoparticles, microbes, seed priming, and hormones

| Mitigation strategy | Salinity level ($dSm^{-1}$) | Application Method/Rate | Mechanism of action/benefits | Key findings/ Impact on Sugar Beet under salinity | References |
|---|---|---|---|---|---|
| γ-Aminobutyric Acid (GABA) treatment | 300 mM NaCl | Exogenous GABA at 1.5 mM L | Enhance antioxidant enzyme activity, gas exchange and fluorescence parameters; bilize photosynthesis and maintain normal growth | Effectively alleviated salt stress damage; improve dry matter accumulation in salt-stress | Yu *et al.*, 2024 |
| $SiO_2$ or MgO nanoparticles | EC soil 1.6. EC water 3.5 | Seed priming and foliar 0, 50, 100, 200 mg $L^{-1}$ | ↑ CAT, POX, PPO, APX; mitigates oxidative stress | Low dose (50 mg $L^{-1}$) improved root traits; $SiO_2$ best for antioxidant enzymes; MgO improved chlorophyll and sucrose accumulation | Ali *et al.*, 2025 |
| Salicylic acid (SA) | 4.5-7.15 | foliar aplication 0, 1000, 2000 ppm | Enhanced root length and LAI | 2000 ppm SA significantly increased top fresh mass and root biomass; SA enhanced sugar yield, sucrose% and purity% | El Gamal *et al.*, 2021 |
| Seed coating | NaCl with osmotic pressure from (-0.4) to (-1.2 dS/m) | Coating with combinations of N, P, K, 6 micronutrients + $GA_3$ + humic acid) | Improved germination and seedling growth with no significant effect on antioxidant enzymes | Treatments improved seedling establishment, and enhanced root and shoot growth | Neamatollahi *et al.*, 2024 |
| Seed priming (hydropriming/ $ZnSO_4$) | NaCl 0, 2, 5, 12 S $m^{-1}$ | ZnSO4 (0.5%) suspension for about 12 hours at 15 °C | ↑ pigments, antioxidant enzymes, proline; better germination indices | Seed priming increased values of germination attributes | Shokouhian and Omidi, 2021 |
| Halotolerant endophytic bacteria | NaCl 0, 50, 150, 300 mM | Inoculation under NaCl with *Pseudomonas stutzeri Kushneria marisflavi* | ↓ $H_2O_2$ and proline; ↑ chlorophyll; growth promotion | Both strains improved growth; *K. marisflavi* generally more effective | Szymańska *et al.*, 2020 |
| Halotolerant PGPR from halophytes | NaCl 50-125 mM | Inoculation (*Micrococcus yunnanensis*, *Planococcus rifietoensis*, *Variovorax paradoxus*) | ACD-producing PGPR; ↓ stress ethylene; ↑ photosynthesis | Enhanced germination, biomass, photosynthetic capacity under saline stress | Zhou *et al.*, 2017 |
| Humic extracts and *Bacillus megaterium* | Saline-sodic soil: EC 9.7-11.3; ESP >15 | Combinations of k-humate, humic acid, fulvic acid, P, and *B. megaterium* | ↓ EC & ESP; ↑ SOM; improved structure (↓ BD) and P availability | Significant shoot/tuber yield increases | El-Atrony *et al.*, 2025 b |
| PGPR[1] + Si nanoparticles (Si-NP) | EC soil 6.9, EC water 5.8 | Inoculation with PGPR (*Pseudomonas koreensis*, *Bacillus coagulans*) + foliar $SiO_2$ NP | decrease oxidative stress indicators (hydrogen peroxide, lipid peroxidation) and sodium ions | Improve growth characteristics, physiological processes, root yield, and sugar yield | Alharbi *et al.*, 2022 |
| Nanoparticles of Titanium Dioxide ($TiO_2$NPs) and Silver Nitrate ($AgNO_3$NPs) + Gibberellic acid | 4.1 | $TiO_2$NPs (100 ppm priming + 200 ppm spray) and $AgNO_3$NPs (30 ppm priming + 75 ppm foliar) | Decrease in potassium, α-amino nitrogen, and sodium in the sugar beet root, influencing nutrient balance and quality | increased sugar yield, total soluble solids, and sugar content | Gomaa *et al.*, 2022 |
| Indole-3-acetic acid (IAA) and Nitrogen (N) | 7.0 | Foliar IAA (0, 150, 300 mg/L) + soil N (240, 290, 340 kg/ha) | Enhance root diameter, leaf fresh weight, and leaf area index; Improves ionic homeostasis (increasing leaf $K^+/Na^+$ and $Ca^{2+}/Na^+$ ratios) | The combination of IAA300 × N340 was the most effective in enhancing root yield and sugar yield | Shaaban *et al.*, 2025 |
| Melatonin (MT) | 300 mM $Na^+$ | Foliar melatonin (0, 30, 60, 90 µM) | Increases antioxidant enzyme activities (SOD, POD, CAT); reduces ROS accumulation; enhances photosynthesis in seedlings | The application of 60 µM melatonin was identified as a feasible way to alleviate salt stress in sugar beet | Liu *et al.*, 2022 |
| Tryptophan priming | 320-800 ppm | Seed soaking in tryptophan (0, 2.5, 5.0 mM) | Tryptophan has a promotive effect on increasing sugar beet yield under water salinity | Pre-soaking in tryptophan (2.5 mM) was the most effective treatment, leading to an increase in all tested growth, yield, and root quality parameters | Hozayn *et al.*, 2020 |
| Allantoin | 100-300 mM Na+ | Exogenous allantoin (0.01, 0.1, 1 mM) | Reduce accumulation of ROS; increase activities of antioxidant enzymes; improve ion homeostasis by decreasing the $Na^+/K^+$ | Exogenous allantoin effectively mitigated salt-adverse effects in a dose-dependent manner, with 0.1 mM being most effective | Liu *et al.*, 2020 |
| PGPR + Proline + salicylic acid | 7.6 | Bacterial Inoculation + proline at 40 g/ha + salicylic acid at 80 g/ha | Combine application enhance root length, root diameter, sugar yield, sucrose% and purity% | Yield, its components (root diameter, sugar yield), and juice quality parameters, enhanced by the bacterial inoculation and inducing material combinations | Mehasen, 2022 |

PGPR= Plant growth-promoting rhizobacteria.

maintenance of membrane integrity, enhanced photosynthetic efficiency, and the regulation of antioxidant enzymes (Miao *et al*., 2020). Additionally, under soil salinity (EC ≈ 4.7 dS $m^{-1}$), soil application of potassium humate (24 kg $ha^{-1}$) combined with foliar application of salicylic acid 100 mg $L^{-1}$, fulvic acid 1.2 kg $ha^{-1}$, hydroxyproline 1000 mg $L^{-1}$increased root yield and sucrose/sugar yield and reduced juice Na; the K-humate 24 kg $ha^{-1}$ + FA + HP combination performed best (Nassar *et al*., 2023).

Exogenous application and seed priming with other plant metabolites have also shown significant effects in alleviating salt tolerance in sugar beet. For example, the application of melatonin (at 60 µM), an hormone-like substance, significantly enhanced the activities of antioxidant enzymes, reduced ROS concentration, and improved photosynthetic efficiency and biomass of sugar beet under salt stress conditions (300 mM $Na^+$) (Liu *et al*., 2022). Similarly, the treatment with γ-aminobutyric acid (GABA), a plant signaling compound, at 1.5 mM has been shown to alleviate salt stress (300 mM $Na^+$) damage in sugar beet by stabilizing membrane integrity, enhancing photosynthetic efficiency, and increasing dry matter accumulation (Yu *et al*., 2024). Also the treatment of sugar beet seedlings subjected to salt stress (300 mM $Na^+$) with another signaling compound, allantoin at 0.1 mM, showed a reduction in salt-induced oxidative damage, a reduced $Na/K^+$ ratio (enhanced homeostasis), and an increased accumulation of osmoprotectants, such as betaine and soluble sugars (Liu *et al*., 2020). Moreover, sugar beet seed pre-soaking in tryptophan (aminoacid precursor) at 2.5 mM under different salinity levels (320 to 8000 ppm), improved chlorophyll pigments, root purity, and overall growth (Hozayn *et al*., 2020). The above findings affirm the potential of plant endogenous metabolites in enhancing sugar beet resilience to salt stress by regulating various physiological and biochemical processes. Further details are provided in Table 3.

## 10. Beneficial soil microorganisms and plant growth stimulators (PGS)

Bioaugmentation with soil microorganisms such as plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF) has shown promising results for sustaining the growth and yield of sugar beet cultivated under salinity stress. For instance, seed and root inoculation with halotolerant endophytic bacteria such as *Pseudomonas stutzeri* and *Kushneria marisflavi* resulted in improved sugar beet growth under saline conditions (up to 300 mM $Na^+$), with *K. marisflavi* showing higher efficiency (Szymańska *et al*., 2020). Growth improvement and salt stress mitigation of these bacterial strains were attributed to increased chlorophyll content and reduced oxidative stress. Similarly, the seed application of two PGPR (*Pseudomonas koreensis* and *Bacillus coagulans*) alone or in combination with foliar application of silica nanoparticles (12.5 mg $L^{-1}$) significantly improved antioxidant activity, decreased ion imbalances (lower K+/Na+ ratio), and enhanced the yield of sugar beet under saline water irrigation and soil salinity (EC 5.7- 6.8) (Alharbi *et al*., 2022). The above results highlight the potential role of PGPR, particularly halotolerant strains, in improving sugar beet productivity under saline conditions.

Synergistic benefits were also achieved by combining microbial inoculation with other PGS, such as humic acid, proline, and salicylic acid, under salinity stress. It has been reported that bacterial inoculation, combined with foliar application of salicylic acid (~80 g $ha^{-1}$) and proline (~40 g $ha^{-1}$), significantly improved root growth, sugar content, and sugar purity under saline soil conditions (EC 8.12 $dSm^{-1}$) (Mehasen, 2022). In another study, inoculation with microorganisms isolated from halophytes, such as *Micrococcus yunnanensis*, *Planococcus rifietoensis*, and *Variovorax paradoxus*, reduced salt-induced stress (up to 150 mM $Na^+$) by improving biomass and photosynthesis under salinity (Zhou *et al*., 2017). Yield of salt-stressed sugar beet and soil characteristics such as EC (9.7-11.3 $dSm^{-1}$) and ESP (15.8%) were enhanced as a result of co-application of *Bacillus megaterium* and humic substances such as fulvic acid and humic acid (El-Atrony *et al*., 2025 b). Inoculation with AMF was also found to be beneficial in mitigating salt stress by enhancing antioxidant activity and stress hormone signaling in sugar beet (Cui *et al*., 2025). These results highlight the crucial role of soil microorganisms in mitigating salt stress and enhancing sugar beet growth through multifaceted mechanisms, including physiological and biochemical effects, as well as improvements in soil quality. Further details are provided in Table 3.

## 11. Seed priming

Seed priming can be used as an effective and practical approach to mitigate salt stress in sugar beet. Priming with sodium selenite ($Na_2SeO_3$) at 20-30 µM significantly improved germination and seedling growth parameters in sugar beet under salinity conditions (300 mM $Na^+$) (Liu *et al*., 2025). Similarly, osmopriming sugar beet seeds with $ZnSO_4$ (0.5%) increased the germination percentage and seedling vigor under salinity levels of up to 12 dS/m (Shokouhian and Omidi, 2021). Seed coating with various combinations of micro- and macronutrients, humic acid, and gibberellic acid resulted in improved germination and seedling growth of sugar beet under drought and saline conditions (NaCl solutions with osmotic pressure up to - 1.2 dS/m) (Neamatollahi *et al*., 2024). Similarly, tryptophan priming (2.5 mM) of sugar beet seeds enhanced germination and seedling growth under salinity conditions (up to 8000 ppm), highlighting the effect of amino acid priming in mitigating abiotic stress in sugar beet (Hozayn *et al*., 2020).

Seed priming can enhance physiological and biochemical processes that contribute to salt tolerance in sugar beet. For example, priming with $Na_2SeO_3$ helped maintain ion homeostasis, increased chlorophyll content, and enhanced antioxidant activity under salt stress (Liu *et al*., 2025). Tryptophan priming (Hozayn *et al*., 2020) also improved chlorophyll a, chlorophyll a/b ratio, and carotenoids, mitigating the impact of salinity on the root quality of sugar beet. Melatonin priming at 60 µM enhanced the salt tolerance of sugar beet by improving antioxidant defenses, reducing reactive oxygen species, and increasing osmolyte accumulation, such as proline and betaine, thereby maintaining higher photosynthetic efficiency in salt-stressed sugar beet (300 m $Na^+$) (Liu *et al*., 2022). Recent advances in the use of nanoparticles, beneficial microbes, seed priming, and plant growth regulators are presented in Table 3.

## 12. Irrigation management

Under salinity conditions, irrigation management optimization can be employed as an effective strategy to sustain sugar beet productivity while preserving precious water resources, particularly in salt-affected semi-arid and arid environments. Regulated deficit irrigation (DI) is an approach to improve water use efficiency (WUE) by reducing the amount of irrigation water below the maximum potential requirements at specific developmental stages. Reportedly, regulated DI (50% FC) combined with optimized N fertilization (150 kg $ha^{-1}$) positively affected the yield, WUE, and photosynthesis of sugar beet, albeit reducing leaf area index (Zhou *et al*., 2022). Similarly, applying DI to sugar beet resulted in improved root dry matter, WUE, and photosynthesis efficiency at a moderate DI level (50% of FC) (Li *et al*., 2019 a). In the formal experiment, it has been demonstrated that rehydration following moderate DI treatment enhanced the allocation of photosynthate to the taproot. In another study, timed water stress (controlled water deficit) suppressed excessive vegetative growth in sugar beet and led to higher yield and improved WUE (Fabeiro *et al*., 2003). Therefore, moderate DI can be used to improve the yield and reduce water consumption in sugar beet production. Li *et al*. (2019 b) have found that moderate DI increased sugar yield by 27% compared to the control treatment (70% of FC), while severe DI (30% of FC) at the phase of storage root development resulted in a 45% improvement in sugar yield. Moreover, both DI levels (30% and 50%) enhanced antioxidant defense, expressed by higher peroxidase activity and proline content after rehydration.

However, the outcomes of deficit irrigation are not always consistent and often highlight a critical trade-off between maximizing absolute yield and optimizing water productivity. The contradiction in results across different studies can be attributed to several factors, including the severity and timing of the water stress, prevailing environmental conditions, the specific sugar beet cultivar, and other interacting agronomic practices. For instance, while the aforementioned studies show yield improvements under specific DI regimes, others demonstrate that maximum yield is still achieved under full irrigation, especially in arid climates. This is illustrated in a study by Yetik and Candoğan (2022), who reported that an irrigation regime replenishing 100% of the soil water depletion resulted in the highest root and sugar yields. In contrast, a 33% DI treatment, while yielding less overall, achieved the highest water productivity. Therefore, moderate DI can be a powerful tool. However, its application must be calibrated to local conditions and specific production goals, whether that be achieving maximum biomass or maximizing the efficiency of water use.

Fewer studies have explicitly tested irrigation strategies under salt stress. In clay saline soil (ECe = 10.1 dS $m^{-1}$) with irrigation waters of 0.5, 1.8, and 3.8 dS $m^{-1}$, shortening the irrigation interval to 2 weeks with fresh water produced the highest root yield and sugar %, while saline water reduced yield and quality; acceptable outcomes were still attainable at short intervals (2-3 weeks) even with saline water (Eid and Ibrahim, 2010). In salt-affected soil (ECe = 10.94 dS $m^{-1}$), combining DI (100/80/60% ETc) with biochar (0/10/20 t $ha^{-1}$) improved soil moisture retention; while water productivity (WP) peaked at 18.18 kg $m^{-3}$ under 80% ETc (El-Samnoudi *et al.*, 2021). Under furrow irrigation, cut-off at 80% of furrow length produced the highest root and sugar yields and the highest WP; improvements in salinity metrics (ECe, SAR, ESP) were greatest with 100% irrigation and least with 70% cut-off (Zoghdan *et al.*, 2019). With saline irrigation water (ECiw = 6.2 vs 0.8 dS $m^{-1}$), high salinity reduced root mass, length, and yield but increased soluble soilds ; similar responses were also observed for irrigation suppression (Costa *et al.*, 2025). This increase is consistent with the stress-induced accumulation of soluble solids (sugars) and earlier root maturation under water deficit (Mahmoud *et al.*, 2018); however, responses can vary with irrigation depth/regime (Ribeiro *et al.*, 2024). Finally, in salt-affected soil (EC 2.9 dSm-1) managed by 80/100/120% pan-evaporation schedules and organic inputs (compost fractions; K-humate 12/24 kg $ha^{-1}$), the 80% pan combined with N fertilization and 24 kg K-humate $ha^{-1}$ improved CEC, soil organic matter, infiltration, hydraulic conductivity, water productivity, and yield (Amer *et al.*, 2020).

## 13. Breeding of salt-tolerant varieties

As demonstrated in the formal sections, cultural practices and agronomic treatments can help alleviate the adverse effects of salinity stress on root yield and sugar yield in sugar beet. However, long-term and sustainable mitigation of salt stress can be achieved by developing salt-resilient sugar beet varieties. In this regard, comparisons of salt-tolerant and salt-sensitive cultivars at the proteomic level can be utilized, particularly for the upregulation of stress proteins, the activity of ROS detoxification, $Na^+$ extrusion, and the accumulation of osmoprotectants (such as betaine) (Wang *et al.*, 2024). Identifying potential salt-stress markers based on physiological and biochemical traits helps screen sugar beet lines to develop new salt-tolerant cultivars.

Sugar beet is considered a salt-tolerant crop; however, high salinity levels negatively affect the growth, development, and yield of sugar beet, particularly at the seedling stage. In an experiment to determine the selection criterion for salt tolerance among three sugar beet cultivars, the proline content, soluble sugar concentration, $Na^+/K^+$ ratio, and $Na^+/Ca^{2+}$ ratio were analyzed and used as criteria to screen for salt stress resistance among the seedlings of the cultivars (Wu *et al.*, 2013). Physiological and proteomic profiles of sugar beet cultivars can also be used to analyze salt tolerance. For instance, proteomic results indicate that salt-sensitive and salt-tolerant cultivars exhibit distinct responses to salinity stress, with the tolerant cultivar showing enhanced antioxidant activity, higher proline content, and lower sodium accumulation (Wang *et al.*, 2019). In another experiment, 11 morphological and physiological traits were used in a cluster analysis to evaluate the salt stress tolerance levels of sugar beet genotypes, and the results were successfully used to identify cultivars as tolerant, moderately tolerant, and sensitive to salt stress (Abbasi, 2020). The identification of reliable and rapid measurable traits is vital for effective salt-stress screening, facilitating selection in breeding programs. In this regard, it has been indicated that chlorophyll content and electrolyte leakage could be used as indicators for selecting salt-tolerant sugar beet cultivars (Kulan *et al.*, 2021).

Polyploidy was also shown to influence the response to salt stress in sugar beet, where diploid genotypes exhibited superior germination, seedling growth, and chlorophyll retention under salt stress compared to triploid and tetraploid genotypes (Aycan *et al.*, 2023). It is also worth mentioning that recent advancements in sugar beet biotechnology have facilitated the development of in vitro regeneration, somatic hybridization, and genetic transformation techniques, such as Agrobacterium-mediated transfer (Mukherjee and Gantait, 2023). These powerful tools can be employed to develop transgenic lines with enhanced tolerance to salt stress (Subrahmanyeswari and Gantait, 2022). In this regard, advanced techniques have been used to rapidly introduce salt tolerance and other stressresilient traits into sugar beet, providing a faster and more precise alternative to conventional breeding methods (Pattanayak *et al*., 2023).

## 14. Research gap and future perspectives

A substantial body of evidence supports the use of mitigation strategies to enhance salinity tolerance in sugar beet, yet several key research gaps remain. It is crucial to first acknowledge a critical limitation across many existing studies: they are often conducted under a wide range of soil conditions (not only varying in salinity) and diverse climates. This variability restricts the direct applicability and generalization of their findings, making it challenging to recommend universal solutions for all saline environments.

Regarding fertilization management, most studies have focused on the effects of individual macro- or micronutrients, with a primary emphasis on potassium, phosphorus, zinc, and molybdenum. Few studies have addressed the synergistic effects of combined nutrient application. There is potential in using strategies that incorporate multiple beneficial elements/nutrients to enhance the physiological responses of sugar beets to salinity by applying a more balanced nutrient regimen. Such integrated management might be more effective in improving nutrient uptake efficiency, ion homeostasis, and osmotic adjustment. Likewise, hormone-like substances, such as salicylic acid, and biostimulants could complement nutrient strategies by enhancing stress adaptation mechanisms in sugar beet. However, comprehensive evaluations of such combined approaches remain scarce, and future research should prioritize the design of experiments that not only evaluate individual strategies but also systematically test combinations of organic amendments, nutrient management, biostimulants, and microbial inoculants. This will be essential to understand their complex interactions and optimize plant responses. Other non-essential but beneficial elements, such as silicon, have also been demonstrated to play a crucial role as an ameliorative agent under saline and drought conditions. To convey the results of these studies as practical solutions, further investigations are needed to examine their optimal form, timing, and dose of application.

Another area that remains understudied is how different sugar beet genotypes respond to specific fertilization strategies under salinity and drought stress**.** Sugar beet genotypes with various levels of salt tolerance may respond differently to fertilization management, particularly when the salinity threshold level is exceeded.

The application of organic amendments, such as compost, biochar, and humic substances, has also shown promising results. However, long-term evaluations of organic amendments remain limited, particularly in terms of their effects on the soil's chemical, physical, and biological properties, which require more attention in future studies. We also note that the optimal type, timing, and rates of application remain poorly defined and require optimization for varying salinity levels in soil and irrigation water. Further investigation is needed to clarify the physiological and biochemical mechanisms, such as enhanced ion uptake, antioxidant activity, and microbe-plant interactions, that contribute to the beneficial effects of organic amendments. In parallel with organic amendments, several emerging tools have also been explored, such as nanoparticles, plant hormones and hormone-like substances, and microbial inoculants, which hold promise in mitigating salt stress in sugar beets. Yet, their combined effects and underlying mechanisms are not well understood. Biostimulants, such as tryptophan seed soaking or the application of hormone-like substances like melatonin, have recently garnered special attention in the literature for their potential to improve photosynthesis and strengthen antioxidant defenses under saline conditions. Further research is needed to evaluate their effectiveness and determine how they may be integrated into comprehensive salinity mitigation strategies for sugar beet.

The combined application of microbial inoculants, such as plant-growth-promoting rhizobacteria (PGPR), nanoparticles, and plant hormones, including auxins, remains largely uninvestigated, primarily due to the limited data available on their effectiveness in mitigating salt stress. While the use of microbial inoculants holds promise, significant knowledge gaps persist. For example, inoculating sugar beets with halotolerant endophytes has been shown to enhance growth under salinity conditions, yet the mechanisms underlying PGPR-mediated stress alleviation and the roles of other symbionts like arbuscular mycorrhizal fungi are still not well understood. Addressing these gaps will require multi-factorial studies to identify potential synergistic or additive effects among microbial inoculants, biostimulants, plant hormones, and beneficial elements/nutrients. Detailed physiological and molecular research will be essential to clarify the tolerance pathways activated by such combinations.

Ultimately, to move beyond isolated findings and develop robust, field-ready solutions, future research programs must be designed to explore the complex interactions between Genotype × Environment × Management (G×E×M). Such studies would provide crucial guidance on which cultivars are best suited to specific saline conditions or respond most effectively to particular agronomic practices. Conducting field-based trials across different sugar beet cultivars, combining microbial inoculation with optimized fertilization and biostimulant treatments, will be crucial for translating experimental findings into practical and scalable solutions for mitigating salinity.

This G×E×M approach will not only test strategies but also help build predictive models that can guide farmers in selecting the optimal combination of cultivar and management practice for their unique environmental challenges.

## References


ABBASI Z., 2020 - *Evaluation of sugar beet monogerm O-type lines for salinity tolerance at vegetative stage.* - Afr. J. Biotechnol., 19(9): 602-612.

ABD EL-MAGEED T.A., EL-SHERIF A.M., ABD EL-MAGEED S.A., ABDOU N.M., 2019 - *A novel compost alleviate drought stress for sugar beet production grown in Cd-contaminated saline soil*. - Agric. Water Manag., 226: 105831.

ABD EL-MAGEED T.A., RADY M.O., SEMIDA W.M., SHAABAN A., MEKDAD A.A., 2021 - *Exogenous micronutrients modulate morpho-physiological attributes, yield, and sugar quality in two salt-stressed sugar beet cultivars*. - J. Soil Sci. Plant Nutr., 21(2): 1421-1436.

ABDEL-SALAM M., ABUZAID A., MOUHMOUD F., ABBAS M.H., 2025 - *Increasing maize productivity in arid sandy soils using combinations of (normal/acidified) biochar and elemental sulfur*. - Egypt. J. Soil Sci., 65(1): 339-357.

ABDOU N.M., EL-SAMNOUDI I.M., IBRAHIM A.E.A.M., EL-TAWWAB A.R.A., 2024 - *Biochar amendment alleviates the combined effects of salinity and drought stress on water productivity, yield and quality traits of Sugar beet (*Beta vulgaris *L.)*. - J. Soil Sci. Plant Nutr., 24(2): 2091-2110.

ABDOU N.M., ROBY M.H.H., AL-HUQAIL A.A., ELKELISH A., SAYED A.A.S., ALHARBI B.M., MAHDY H.A.A., ABOU-SREEA A.I.B., 2023 - *Compost improving morphophysiological and biochemical traits, seed yield, and oil quality of* Nigella sativa *under drought stress.* - Agronomy, 13: 1147.

ABU-ELLAIL F.F.B., SASY A.H., 2021 - *GT biplot analysis for yield and related traits in some sugar beet varieties as affected by compost under saline soil*. - Egypt. J. Appl. Sci., 36(3): 66-83.

AHMED B.O., YAMAMOTO T., RASIAH V., INOUE M., ANYOJI H., 2007 - *The impact of saline water irrigation management options in a dune sand on available soil water and its salinity.* - Agric. Water Manag., 88(1-3): 63-72.

ALHARBI K., HAFEZ E., OMARA A.E.D., AWADALLA A., NEHELA Y., 2022 - *Plant growth promoting rhizobacteria and silica nanoparticles stimulate sugar beet resilience to irrigation with saline water in salt-affected soils.* - Plants, 11(22): 3117.

ALI A.S., ELSHAMY H., DYAB M., HAROUN S., EL-MEHASSEB I., 2025 - *Nanoparticles enhance antioxidant system and improve yield quality of sugar beet (*Beta vulgaris *L.) plants irrigated with wastewater.* - Egypt. J. Soil Sci., 65(2).

ALKHARABSHEH H.M., SELEIMAN M.F., BATTAGLIA M.L., SHAMI A., JALAL R.S., ALHAMMAD B.A., AL-SAIF A.M., 2021 - *Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review.* - Agronomy, 11: 993.

AMER M., GAIZA S., ABOU EL SOUD H., RASHAD S., 2020 - *Contribution of management of irrigation water and organic application in improving some soil properties and its water productivity of sugar beet and cotton.* - Environ. Biodivers. Soil Secur., 4(Issue 2020): 7-18.

ASHRAFI E., RAZMJOO J., ZAHEDI M., 2018 - *Effect of salt stress on growth and ion accumulation of alfalfa (*Medicago sativa *L.) cultivars.* - J. Plant Nutr., 41(7): 818-831.

AYCAN M., ERKILIC E.G., OZGEN Y., POYRAZ I., YILDIZ M., 2023 - *The response of sugar beet (*Beta vulgaris *L.) genotypes at different ploidy levels to salt (NaCl) stress.* - Int. J. Plant Biol., 14(1): 199-217.

BOURAS H., BOUAZIZ A., BOUAZZAMA B., HIRICH A., CHOUKR-ALLAH R., 2021 - *How phosphorus fertilization alleviates the effect of salinity on sugar beet (*Beta vulgaris *L.) productivity and quality*. - Agronomy, 11(8): 1491.

BRAR N.S., DHILLON B.S., SAINI K.S., SHARMA P.K., 2015 - *Agronomy of sugarbeet cultivation - A review.* - Agric. Rev., 36(3): 184-197.

CARR M.K.V., KNOX J.W., 2011 - *The water relations and irrigation requirements of sugar cane (*Saccharum officinarum*): A review.* - Exp. Agric., 47(1): 1-25.

COSTA F.H., AZEVEDO B.M.D., SOUSA G.G.D., SOUSA L.V.D., FERNANDES C.N., PINTO O.R.D.O., FRAZÃO D.S., 2025 - *Interval of irrigation suppression in beet cultivation under salt stress.* - Rev. Bras. Eng. Agríc. Ambient., 29(9): e289926.

CUI Z., LI X., HAN P., CHEN R., DONG Y., GENG G., WANG Y., 2025 - *Integrative transcriptomic and physiological analyses uncover mechanisms by which arbuscular mycorrhizal fungi mitigate salt stress in sugar beet.* - Mycorrhiza, 35(3): 1-19.

DAOUD S., HARROUNI C., HUCHZERMEYER B., KOYRO H.W., 2008 - *Comparison of salinity tolerance of two related subspecies of* Beta vulgaris*: The sea beet (*Beta vulgaris *ssp.* maritima*) and the sugar beet (*Beta vulgaris *ssp.* vulgaris*)*, pp. 115-129. - In: ABDELLY C., M. ÖZTÜRK, M. ASHRAF, and C. GRIGNON (eds.) *Biosaline agriculture and high salinity tolerance*. Birkhäuser Verlag, Basel, Switzerland, pp. 367.

EID S.M., IBRAHIM M.M., 2010 - *Irrigation water salinity and irrigation intervals effects on growth, yield and quality of sugar beet in saline soil at Middle North Nile Delta*. - J. Soil Sci. Agric. Eng., 1(8): 789-800.

EL-ATRONY D., FARID I.M., EL-GHOZOLI M., ABBAS M.H., 2025 a - *Sustainable enhancement of sugar beet productivity in salt-affected soils using humic substances and Bacillus biofertilizers*. - Environ. Biodivers. Soil Secur., 9(2025).

EL-ATRONY D., FARID I.M., EL-GHOZOLI M., ABBAS M.H., 2025 b - *Can humic extracts and Bacillus megaterium boost sugar beet productivity in a saline-sodic soil?* - Egypt. J. Soil Sci., 65(2).

EL-GAMAL I.S.H., EL-SAFY N.K., ABO-MARZOKA E.A., 2021 - *Growth of some sugar beet varieties under different locations as affected by foliar application with salicylic acid on yield and quality.* - Egypt. Acad. J. Biol. Sci. H. Botany, 12(1): 161-173.

EL-KADY M.S., ABU-ELLAIL F.F., EL-LABOUDY E.H.S., 2021 - *Evaluation of some sugar beet varieties under water salinity stress in new reclaimed land*. - J. Plant Prod., 12(1): 63-72.

EL-MAGEED T.A.A., MEKDAD A.A., RADY M.O., ABDELBAKY A.S., SAUDY H.S., SHAABAN A., 2022 - *Physio-biochemical and agronomic changes of two sugar beet cultivars grown in saline soil as influenced by potassium fertilizer*. - J. Soil Sci. Plant Nutr., 22(3): 3636-3654.

EL-SAMNOUDI I., IBRAHIM A.E.A., ABD EL-TAWWAB A., ABDOU N., 2021 - *Addition biochar to enhanced soil quality and sugar beet crop grown under water stress treatments in salt-affected soils.* - Fayoum J. Agric. Res. Dev., 35(3): 478-494.

FABEIRO C., DE SANTA OLALLA F.M., LOPEZ R., DOMÍNGUEZ A., 2003 - *Production and quality of the sugar beet (*Beta vulgaris *L.) cultivated under controlled deficit irrigation conditions in a semi-arid climate.* - Agric. Water Manag., 62(3): 215-227.

FAUST F., SCHUBERT S., 2017 - In vitro *protein synthesis of sugar beet (*Beta vulgaris*) and maize (*Zea mays*) is differentially inhibited when potassium is substituted by sodium.* - Plant Physiol. Biochem., 118: 228-234.

FLOWERS T.J., 2004 - *Improving crop salt tolerance.* - J. Exp. Bot., 55(396): 307-319.

GADELHA B.B., FREIRE M.H.D.C., SOUSA H.C., COSTA F.H., LESSA C.I., SOUSA G.G.D., 2021 - *Growth and yield of beet irrigated with saline water in different types of vegetable mulching.* - Rev. Bras. Eng. Agríc. Ambient., 25(12): 847-852.

GHORBANI M., AMIRAHMADI E., KONVALINA P., MOUDRÝ J., BÁRTA J., KOPECKÝ M., BUCUR R.D., 2022 - *Comparative influence of biochar and zeolite on soil hydrological indices and growth characteristics of corn (*Zea mays *L.).* - Water, 14(21): 3506.

GHOULAM C., FARES K., 2001 - *Effect of salinity on seed germination and early seedling growth of sugar beet (*Beta vulgaris *L.).* - Seed Sci. Technol., 29: 357-364.

GOLDMAN I.L., JANICK J., 2021 - *Evolution of root morphology in table beet: historical and iconographic*. - Front. Plant Sci., 12: 689926.

GOMAA M.A., EL-GENDY B.A., FAWAZ S.A., KANDIL E.E., 2022 - *Sugar beet productivity and quality as affected by some nanoparticles and gibberellic acid under soil as affected by salinity.* - Egypt. Acad. J. Biol. Sci., H Bot., 13(2): 195-206.

GUMIENNA M., SZWENGIEL A., SZCZEPAŃSKA-ALVAREZ A., SZAMBELAN K., LASIK-KURDYŚ M., CZARNECKI Z., SITARSKI A., 2016 - *The impact of sugar beet varieties and cultivation conditions on ethanol productivity.* - Biomass Bioenergy, 85: 228-234.

HAFEZ E.M., OSMAN H.S., GOWAYED S.M., OKASHA S.A., OMARA A.E.D., SAMI R., ABD EL-RAZEK U.A., 2021 - *Minimizing the adversely impacts of water deficit and soil salinity on maize growth and productivity in response to the application of plant growth-promoting rhizobacteria and silica nanoparticles.* - Agronomy, 11(4): 676.

HAIDER I., RAZA M.A.S., IQBAL R., ASLAM M.U., HABIB-UR-RAHMAN M., RAJA S., AHMAD S., 2020 - *Potential effects of biochar application on mitigating the drought stress implications on wheat (*Triticum aestivum *L.) under various growth stages.* - J. Saudi Chem. Soc., 24(12): 974-981.

HOZAYN M., ABD-ELMONEM A.A., SAMAHA G.M., 2020 - *The physiological effect of pre-soaking with tryptophan on sugar beet (*Beta vulgaris *L.) productivity under different levels of salinity stresses.* - Bull. Natl. Res. Cent., 44(1): 65.

HUSSAIN Z., KHATTAK R.A., IRSHAD M., MAHMOOD Q., 2014 - *Sugar beet (*Beta vulgaris *L.) response to diammonium phosphate and potassium sulphate under saline-sodic conditions*. - Soil Use Manag., 30(3): 320-327.

JIN F., PIAO J., MIAO S., CHE W., LI X., LI X., LAN Y., 2024 - *Long-term effects of one-off biochar application on soil physicochemical properties, salt concentration, nutrient availability, enzyme activity, and rice yield in highly* *saline-alkali paddy soils: a 6-year field experiment*. - Biochar, 6(1): 40.

KANDIL A., BADAWI M.A., SEADH S.E., ARAFAT H.S., 2023 - *Using some natural substances to improve seedlings parameters of sugar beet under salinity conditions.* - J. Plant Production, 14(4): 211-217.

KULAN E.G., ARPACIOĞLU A., ERGIN N., KAYA M.D., 2021 - *Evaluation of germination, emergence and physiological properties of sugar beet cultivars under salinity.* - Trakya Univ. J. Nat. Sci., 22(2): 263-274.

LI Y., FAN H., SU J., FEI C., WANG K., TIAN X., MA F., 2019 b - *Regulated deficit irrigation at special development stages increases sugar beet yield.* - Agron. J., 111(3): 1293-1303.

LI Y., LIU N., FAN H., SU J., FEI C., WANG K., KISEKKA I., 2019 a - *Effects of deficit irrigation on photosynthesis, photosynthate allocation, and water use efficiency of sugar beet.* - Agric. Water Manag., 223: 105701.

LIU A., WANG H., WANG M., 2025 - *$Na_2SeO_3$ seed priming improves seed germination, seedling growth and rhizosphere microbial community structure of Sugar Beet (*Beta vulgaris *L.) under salt stress.* - Plant Stress, 16: 100795.

LIU H.U.A., WANG Q., YU M., ZHANG Y., WU Y., ZHANG H., 2008 - *Transgenic salt-tolerant sugar beet (*Beta vulgaris *L.) constitutively expressing an* Arabidopsis thaliana *vacuolar $Na^+/H^+$ antiporter gene, AtNHX3, accumulates more soluble sugar but less salt in storage roots.* - Plant Cell Environ., 31(9): 1325-1334.

LIU L., LIU D., WANG Z., ZOU C., WANG B., ZHANG H., LI C., 2020 - *Exogenous allantoin improves the salt tolerance of sugar beet by increasing putrescine metabolism and antioxidant activities.* - Plant Physiol. Biochem., 154: 699-713.

LIU L., WANG Z., GAI Z., WANG Y., WANG B., ZHANG P., LI C., 2022 - *Exogenous application of melatonin improves salt tolerance of sugar beet (*Beta vulgaris *L.) seedlings.* - Acta Physiol. Plant., 44(6): 57.

LV X., CHEN S., WANG Y., 2019 - *Advances in understanding the physiological and molecular responses of sugar beet to salt stress.* - Front. Plant Sci., 10: 1431.

MAHMOUD E.S.A., HASSANIN M.A., BORHAM T.I., EMARA E.I., 2018 - *Tolerance of some sugar beet varieties to water stress*. - Agric. Water Manag., 201: 144-151.

MEHASEN S.A., 2022 - *Productivity and quality of some sugar beet varieties as affected by bacterial inoculation and inducing materials in saline soil.* - Ann. Agric. Sci. Moshtohor, 60(4): 1045-1050.

MEKDAD A.A., SHAABAN A., RADY M.M., ALI E.F., HASSAN F.A., 2021 - *Integrated application of K and Zn as an avenue to promote sugar beet yield, industrial sugar quality, and K-use efficiency in a salty semi-arid agro-ecosystem*. - Agronomy, 11(4): 780.

MERWAD A.R.M., 2016 - *Efficiency of potassium fertilization and salicylic acid on yield and nutrient accumulation of sugar beet grown on saline soil*. - Commun. Soil Sci. Plant Anal., 47(9): 1184-1192.

MIAO Y., LUO X., GAO X., WANG W., LI B., HOU L., 2020 - *Exogenous salicylic acid alleviates salt stress by improving leaf photosynthesis and root system architecture in cucumber seedlings.* - Sci. Hortic., 272: 109577.

MOSAAD I.S., SERAG A.H., SHETA M.H., 2022 - *Promote sugar beet cultivation in saline soil by applying humic substances in-soil and mineral nitrogen fertilization*. - J. Plant Nutr., 45(16): 2447-2464.

MUKHERJEE E., GANTAIT S., 2023 - *Genetic transformation in sugar beet (*Beta vulgaris *L.): technologies and applications.* - Sugar Tech, 25(2): 269-281.

MULET J.M., CAMPOS F., YENUSH L., 2020 - *Ion homeostasis in plant stress and development.* - Front. Plant Sci., 11: 618273.

MUNNS R., 2002 - *Comparative physiology of salt and water stress.* - Plant Cell Environ., 25(2): 239-250.

NASSAR M.A.A., EL-MAGHARBY S.S., IBRAHIM N.S., KANDIL E.E., ABDELSALAM N.R., 2023 - *Productivity and quality variations in sugar beet induced by soil application of K-Humate and foliar application of biostimulants under salinity condition*. - J. Soil Sci. Plant Nutr., 23(3): 3872-3887.

NEAMATOLLAHI E., MOHAMMADI M., AFSHARI R.T., 2024 - *Assessing of sugar beet seed adaptation under salt and drought stress conditions with coating technology based on Fuzzy inference system.* - Heliyon, 10(19).

NEMEAT ALLA H., 2023 - *Yield and quality of sugar beet as affected by potassium and salicylic acid fertilization levels in saline soil*. - Environ. Biodivers. Soil Secur., 7(2023): 193-204.

OSMAN H.S., RADY A.M., AWADALLA A., OMARA A.E.D., HAFEZ E.M., 2022 - *Improving the antioxidants system, growth, and sugar beet quality subjected to long-term osmotic stress by phosphate solubilizing bacteria and compost tea*. - Int. J. Plant Prod., 16(1): 119-135.

OTHMAN Y.A., HANI M.B., AYAD J.Y., ST HILAIRE R., 2023 - *Salinity level influenced morpho-physiology and nutrient uptake of young citrus rootstocks.* - Heliyon, 9(2).

PATTANAYAK S., DAS S., KUMAR S., 2023 - *Development of stress tolerant transgenomic traits in sugar beet through biotechnological application.* - J. Plant Protect. Res., 1-12.

PEREIRA FILHO J.V., VIANA T.V.D.A., SOUSA G.G.D., CHAGAS K.L., AZEVEDO B.M.D., PEREIRA C.C.D.S., 2019 - *Physiological responses of lima bean subjected to salt and water stresses.* - Rev. Bras. Eng. Agríc. Ambient., 23(12): 959-965.

RASOULI F., KIANI-POUYA A., LI L., ZHANG H., CHEN Z., HEDRICH R., SHABALA S., 2020 - *Sugar beet (*Beta vulgaris*) guard cells responses to salinity stress: a proteomic analysis.* - Int. J. Mol. Sci., 21(7): 2331.

RAŠOVSKÝ M., PAČUTA V., DUCSAY L., LENICKÁ D., 2022 -

*Quantity and quality changes in sugar beet (*Beta vulgaris *Provar. Altissima Doel) induced by different sources of biostimulants.* - Plants, 11: 2222.

RIBEIRO R.M.R., SOUSA G.G., BARBOSA A.S., MATOS E.C., VIANA T.V.A., LEITE K.N., SANTOS S.O., 2024 - *The impact of saline and water stress on the agronomic performance of beet crops*. - Braz. J. Biol., 84: e276278.

ROZEMA J., CORNELISSE D., ZHANG Y., LI H., BRUNING B., KATSCHNIG D., VAN BODEGOM P., 2015 - *Comparing salt tolerance of beet cultivars and their halophytic ancestor: consequences of domestication and breeding programmes.* - AoB Plants, 7: 83.

RUSSELL B.L., RATHINASABAPATHI B., HANSON A.D., 1998 - *Osmotic stress induces expression of choline monooxygenase in sugar beet and amaranth.* - Plant Physiol., 116(2): 859-865.

SARAVANAN A., KUMAR P.S., 2022 - *Biochar derived carbonaceous material for various environmental applications: Systematic review.* - Environ. Res., 214: 113857.

SHAABAN A., ABDOU N.M., ABD EL-MAGEED T.A., SEMIDA W.M., ABD EL TAWWAB A.R., MOHAMED G.F., HEMIDA K.A., 2025 - *Foliar fertilization with potassium silicate enhances water productivity and drought resilience in sugar beet*. - Field Crops Res., 326: 109840.

SHABANA M.M., AL-HUQAIL A.A., ALLA H.E.N., KHEIR A.M., EL-SHARKAWY M., 2024 - *Enhancing soil resilience and sugar beet (*Beta vulgaris *L.) yield: Mid-term effects of compost and glauconite integration*. - J. Agron. Crop Sci., 210(5): e12747.

SHEIKH A.H., ZACHARIA I., TABASSUM N., HIRT H., NTOUKAKIS V., 2024 - *14-3-3 proteins as a major hub for plant immunity.* - Trends Plant Sci., 29(11): 1245-1253.

SHOKOUHIAN A., OMIDI H., 2021 - *Sugar beet (*Beta vulgaris *L.) germination indices and physiological properties affected by priming and genotype under salinity stress.* - Not. Bot. Horti Agrobot. Cluj-Napoca, 49(3): 12063.

SILVA S.S.D., LIMA G.S.D., DE LIMA V.L., GHEIYI H.R., SOARES L.A.D.A., OLIVEIRA J.P., 2022 - *Production and post-harvest quality of mini-watermelon crop under irrigation management strategies and potassium fertilization.* - Rev. Bras. Eng. Agríc. Ambient., 26: 51-58.

SINGH A., RAWAT S., RAJPUT V.D., MINKINA T., MANDZHIEVA S., ELOYAN A., SINGH R.K., SINGH O., EL-RAMADY H., GHAZARYAN K., 2024 - *Nanotechnology products in agriculture and environmental protection: advances and challenges.* - Egypt. J. Soil Sci., 64(4): 1355-1378.

SINGH H., NORTHUP B.K., RICE C.W., PRASAD P.V.V., 2022 - *Biochar applications influence soil physical and chemical properties, microbial diversity, and crop productivity: a meta-analysis.* - Biochar, 4: 8.

SIUDA A., ARTYSZAK A., GOZDOWSKI D., AHMAD Z., 2023 - *Effect of form of silicon and the timing of a single foliar application on sugar beet yield*. - Agriculture, 14(1): 86.

SKORUPA M., GOŁĘBIEWSKI M., KURNIK K., NIEDOJADŁO J., KĘSY J., KLAMKOWSKI K., TYBURSKI J., 2019 - *Salt stress vs. salt shock - the case of sugar beet and its halophytic ancestor.* - BMC Plant Biol., 19(1): 57.

SOROUR S.G.H.R., MOSALEM M.E., ABOTALEB A.A.N., GHARIEB A.S., 2021 - *Alleviation of salt-stress on sugar beet (*Beta vulgaris *L.) using molasses, humic, and nano-*$CaCO_3$. - Appl. Ecol. Environ. Res., 19(6).

STEVANATO P., BIAGGI M.D., SKARACIS G.N., COLOMBO M., MANDOLINO G., BIANCARDI E., 2001 - *The sea beet (*Beta vulgaris *L. ssp.* maritima*) of the Adriatic coast as source of resistance for sugar beet.* - Sugar Tech, 3(3): 77-82.

SU J.Y., LIU C.H., TAMPUS K., LIN Y.C., HUANG C.H., 2022 - *Organic amendment types influence soil properties, the soil bacterial microbiome, and tomato growth.* - Agronomy, 12: 1236.

SUBRAHMANYESWARI T., GANTAIT S., 2022 - *Advancements and prospectives of sugar beet (*Beta vulgaris *L.) biotechnology.* - Appl. Microbiol. Biotechnol., 106(22): 7417-7430.

SZYMAŃSKA S., TYBURSKI J., PIERNIK A., SIKORA M., MAZUR J., KATARZYNA H., 2020 - *Raising beet tolerance to salinity through bioaugmentation with halotolerant endophytes.* - Agronomy, 10(10): 1571.

TOMCZYK A., SOKOŁOWSKA Z., BOGUTA P., 2020 - *Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects.* - Rev. Environ. Sci. Biotechnol., 19(1): 191-215.

VAN ZELM E., ZHANG Y., TESTERINK C., 2020 - *Salt tolerance mechanisms of plants.* - Annu. Rev. Plant Biol., 71(1): 403-433.

WAKEEL A., SÜMER A., HANSTEIN S., YAN F., SCHUBERT S., 2011 - In vitro *effect of different* $Na^+/K^+$ *ratios on plasma membrane* $H^+$*-ATPase activity in maize and sugar beet shoot.* - Plant Physiol. Biochem., 49(3): 341-345.

WANG Y., LIU H., WANG M., LIU J., GENG G., WANG Y., 2024 - *Salt tolerance in sugar beet: From impact analysis to adaptive mechanisms and future research*. - Plants, 13(21): 3018.

WANG Y., STEVANATO P., LV C., LI R., GENG G., 2019 - *Comparative physiological and proteomic analysis of two sugar beet genotypes with contrasting salt tolerance.* - J. Agric. Food Chem., 67(21): 6056-6073.

WANG Y., STEVANATO P., YU L., ZHAO H., SUN X., SUN F., GENG G., 2017 - *The physiological and metabolic changes in sugar beet seedlings under different levels of salt stress.* - J. Plant Res., 130(6): 1079-1093.

WANG Y., ZHAN Y., WU C., GONG S., ZHU N., CHEN S., LI H., 2012 - *Cloning of a cystatin gene from sugar beet M14 that can enhance plant salt tolerance.* - Plant Sci., 191: 93-99.

WU G.Q., LIANG N., FENG R.J., ZHANG J.J., 2013 - *Evaluation of salinity tolerance in seedlings of sugar beet (*Beta vulgaris *L.) cultivars using proline, soluble* *sugars and cation accumulation criteria.* - Acta Physiol. Plant., 35(9): 2665-2674.

WU G.Q., LIN L.Y., JIAO Q., LI S.J., 2019 - *Tetraploid exhibits more tolerant to salinity than diploid in sugar beet (*Beta vulgaris *L.)*. - Acta Physiol. Plant., 41(4): 52.

YANG A., AKHTAR S.S., IQBAL S., AMJAD M., NAVEED M., ZAHIR Z.A., JACOBSEN S.E., 2016 - *Enhancing salt tolerance in quinoa by halotolerant bacterial inoculation.* - Funct. Plant Biol., 43(7): 632-642.

YANG L., MA C., WANG L., CHEN S., LI H., 2012 - *Salt stress induced proteome and transcriptome changes in sugar beet monosomic addition line M14.* - J. Plant Physiol., 169(9): 839-850.

YETIK A.K., CANDOĞAN B.N., 2022 - *Optimisation of irrigation strategy in sugar beet farming based on yield, quality and water productivity.* - Plant Soil Environ., 68(8).

YOLCU S., ALAVILLI H., GANESH P., PANIGRAHY M., SONG K., 2021 - *Salt and drought stress responses in cultivated beets (*Beta vulgaris *L.) and wild beet (*Beta maritima *L.)*. - Plants, 10(9): 1843.

YU B., LI J., KOH J., DUFRESNE C., YANG N., QI S., LI H., 2016 - *Quantitative proteomics and phosphoproteomics of sugar beet monosomic addition line M14 in response to salt stress.* - J. Proteomics, 143: 286-297.

YU X., WANG X., ZHANG P., CHEN J., GU W., WANG Y., 2024 - *Exogenous γ-Aminobutyric Acid (GABA) regulates the response of sugar beet seedlings to salt stress through GABA branched metabolism.* - J. Plant Growth Regul., 44: 2977-2994.

ZEWAIL R.M.Y., EL-GMAL I.S., KHAITOV B., EL-DESOUKY H.S., 2020 - *Micronutrients through foliar application enhance growth, yield and quality of sugar beet (*Beta vulgaris *L.).* - J. Plant Nutr., 43(15): 2275-2285.

ZHANG P., LIU L., WANG X., WANG Z., ZHANG H., CHEN J., LI C., 2021 - *Beneficial effects of exogenous melatonin on overcoming salt stress in sugar beets (*Beta vulgaris *L.).* - Plants, 10(5): 886.

ZHAO C., ZHANG H., SONG C., ZHU J.K., SHABALA S., 2020 - *Mechanisms of plant responses and adaptation to soil salinity.* - Innov., 1(1): 100017.

ZHOU H., XU P., ZHANG L., HUANG R., ZHANG C., XIANG D., FAN H., 2022 - *Effects of regulated deficit irrigation combined with optimized nitrogen fertilizer management on resource use efficiency and yield of sugar beet in arid regions.* - J. Clean. Prod., 380: 134874.

ZHOU N., ZHAO S., TIAN C.Y., 2017 - *Effect of halotolerant rhizobacteria isolated from halophytes on the growth of sugar beet (*Beta vulgaris *L.) under salt stress.* - FEMS Microbiol. Lett., 364(11).

ZOGHDAN M., AIAD M., SHABANA M., ABOELSOUD H., 2019 - *Improvement of soil and water productivity for sugar beet under salt affected soils at North Nile Delta, Egypt.* - J. Soil Sci. Agric. Eng., 10(1): 41-50.