Plant Growth Promoting Rhizobacteria and Silica Nanoparticles Stimulate Sugar Beet Resilience to Irrigation with Saline Water in Salt-Affected Soils

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Abstract: Combined stressors (high soil salinity and saline water irrigation) severely reduce plant growth and sugar beet yield. Seed inoculation with plant growth-promoting rhizobacteria (PGPR) and/or foliar spraying with silica nanoparticles (Si-NP) is deemed one of the most promising new strategies that have the potential to inhibit abiotic stress. Herein, sugar beet (Beta vulgaris) plants were treated with two PGPR (Pseudomonas koreensis MG209738 and Bacillus coagulans NCAIM B.01123) and/or Si-NP, during two successive seasons 2019/2020 and 2020/2021 to examine the vital role of PGPR, Si-NP, and their combination in improving growth characteristics, and production in sugar beet plants exposed to two watering treatments (fresh water and saline water) in salt-affected soil. The results revealed that combined stressors (high soil salinity and saline water irrigation) increased ion imbalance (K+ /Na+ ratio; from 1.54 ± 0.11 to 1.00 ± 0.15) and declined the relative water content (RWC; from 86.76 ± 4.70 to 74.30 ± 3.20%), relative membrane stability index (RMSI), stomatal conductance (gs), and chlorophyll content, which negatively affected on the crop productivity. Nevertheless, the application of combined PGPR and Si-NP decreased oxidative stress indicators (hydrogen peroxide and lipid peroxidation) and sodium ions while increasing activities of superoxide dismutase (SOD; up to 1.9-folds), catalase (CAT; up to 1.4-folds), and peroxidase (POX; up to 2.5-folds) enzymes, and potassium ions resulting in physiological processes, root yield, and sugar yield compared to non-treated controls under combined stressors (high soil salinity and saline water irrigation). It is worth mentioning that the singular application of PGPR improved root length, diameter, and yield greater than Si-NP alone and it was comparable to the combined treatment (PGPR+Si-NP). It was concluded that the combined application of PGPR and Si-NP has valuable impacts on the growth and yield of sugar beet growing under combined stressors of high soil salinity and saline water irrigation.

Keywords: oxidative stress; Beta vulgaris; silica nanoparticles; plant growth promoting rhizobacteria; soil salinity; irrigation with saline

1. Introduction

Sugar beet (Beta vulgaris L.) is believed to be the second most imperative crop worldwide, after sugarcane, which is mainly a multi-use crop cultivated in many countries as an industrial crop for the production of sucrose [1]. In Egypt, the sugar beet crop was grown in a total area of 280.25 ha. (13.56 t ha −1 production) during the 2020/2021 season with...
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an average root yield of 50.36 t ha$^{-1}$ [2]. The sugar beet crop can grow in arable lands in addition to low-quality soils [3]. The national strategy for sustainable development for the cultivation and production of the sugar beet crop is to expand sugar beet cultivation in salt-affected soil and irrigation with low-quality water where some nutrients, particularly micro-nutrients, are deficient which are required for higher growth and productivity [4]. Despite the importance of sugar beet as a high-income crop for farmers, some of them still do not have sufficient experience to cultivate it; therefore, it is important to pay attention to this problem and develop strategies to solve it to improve growth under difficult conditions, which has a noticeable impact on increasing productivity [5].

Soil salinity and irrigation with poor-quality water are the main worldwide conundrums that severely affect sustainable agriculture, mainly in arid and semi-arid regions which decrease crop growth by more than 70% [6]. Worldwide, approximately 800 million hectares of land are estimated to be salinity- (397 Mha) or sodicity-affected (434 Mha). In addition, the utilization of irrigation with saline water in saline soils is considered a great challenge for plant growth and development [7]. The growth of plants irrigated with saline water and/or grown in salt-affected soil is negatively affected, due to oxidative stress, and nutritional discharge because of raised Na$^+$ and Cl$^-$ ions and soil dispersion resulting in the limiting of sustainable agricultural production [8]. One of the characteristics of the sugar crop is its tolerance to salinity [9]. The sugar beet crop has the potential to withstand soil electrical conductivity (E.C.) to 7.0 dS m$^{-1}$. However higher soil salinity in corporations with irrigation with saline water has an injurious impact on the root, sugar yield, and juice quality [10].

Having in mind the above-mentioned facts, recently, agricultural policy has allowed several strategies such as plant growth-promoting rhizobacteria (PGPR) and nanotechnology to enhance the growth and productivity of field crops [11]. One such accepted approach is the use of plant growth regulators that farmers have implemented to be sustainable and cheaper as well as eco-friendly [12]. Plant growth-promoting rhizobacteria (PGPR) is deemed an alternative viable technology for enhancing plant growth and productivity [13]. PGPR as bio-fertilizers could promote plant development in various ways, such as nitrogen fixation, solubilization of phosphorus, or phyto-stimulators, that rely on PGPR species [14]. *Pseudomonas* and *Bacillus* are the most widely stated genera that are used as stress-tolerant PGPR [15] which can improve morpho-physiological characteristics under environmental stressors by different direct and indirect techniques such as producing exopolysaccharides (EPS) which prevent Na$^+$ flux and decline its absorption in plants [16]. This is positively reflected in $N_2$ fixation and phosphate solubilization by binding free phosphorus in non-legumes and improving nutrient uptake [17]. Seed inoculation with PGPR could mitigate the adverse effects of salt stress via the production of phytohormones, i.e., auxins (IAA), gibberellins (GA), cytokinins, and abscisic acid that has the potential to promote the systemic tolerance, as well as producing stress-induced ethylene [17].

An alternative sustainable technology in crop production is the use of nanoparticles as foliar spraying such as silicon nanoparticles (Si-NP). Si-NP has recently received great attention because of its potential to alleviate the adverse impacts of abiotic stresses [18]. Soil Amendment proved recently a positive effect on plant growth and development under soil salinity conditions due to making the nutrient flow available and moving faster to stomata pore sizes when applied in small concentrations [19]. Silica application could increase normal sugar beet growth by improving root growth, and morpho-physiological attributes along with sugar yield. Moreover, silicon application as nanocomposites could improve the antioxidant defense system, whilst declining oxidative stress, decrement Na$^+$ uptake, and incrementing K$^+$ uptake [20]. Foliar spraying with Si-NP improved the CO$_2$ assimilation rate in plants by enhancing stomatal conductance ($g_S$) in leaves leading to declined water loss through transpiration [21]. Consequently, we suppose that foliar spraying with Si-NP has a positive effect on plant growth and development under soil salinity conditions [22]. Little studies have focused on the physiological effect of Si-NP in sugar beet.
Having in mind the above-mentioned facts, the coupling of plant growth-promoting rhizobacteria (PGPR) and silica nanoparticles (Si-NP) has not been examined together to determine whether the motivating impacts of treatments (PGPR and Si-NP), could increase morpho-physiological processes under saline soil and irrigation with saline water. The current investigation was performed to assess the effect of singular and combination treatments of PGPR (Pseudomonas koreensis MG209738 and Bacillus coagulans NCIBM B.01123) and Si-NP on improving sugar beet physiological and biochemical attributes along with the antioxidant enzyme activity and sugar beet productivity under harsh environmental conditions.

2. Results

2.1. Seed Inoculation with PGPR and Si-NP Foliar Application Enhanced the Growth of Sugar Beet Plants under Water Salinity Stress

Although irrigation of sugar beet plants using saline water significantly ($P_{\text{Irrigation}} < 0.0001$) reduced the leaf area per plant (Figures 1A and S1A), root length (Figures 1B and S1B), and root diameter (Figures 1C and S1C) during both 2019/2020 and 2020/2021 seasons, respectively, compared with the regularly irrigated beet plants, seed inoculation with plant growth-promoting rhizobacteria (PGPR) or silica nanoparticles (Si-NP) foliar application or their combination significantly ($P_{\text{Treatment}} < 0.0001$) enhanced all studied growth parameters (Figure 1). In both seasons, seed inoculation with PGPR individually greatly enhanced the leaf area per plant ($P_{\text{Irrigation}} \times \text{Treatment} = 0.0009$ in the 2019/2020 season and $P_{\text{Irrigation}} \times \text{Treatment} = 0.0106$ in 2020/2021 season) than Si-NP foliar application. However, the combined application of PGPR and Si-NP had the highest leaf area per plant, as well as root length, and root diameter during the 2019/2020 and 2020/2021 seasons when sugar beet plants were irrigated with fresh or even stressed with saline water.

Figure 1. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the growth of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 season. (A) Leaf area per plant (dm$^2$), (B) root length (cm), and (C) root diameter (cm) during the 2019/2020 season, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test ($P_{\text{Irrigation}} \times \text{Treatment} \leq 0.05$).
2.2. PGPR and Si-NP Application Augmented the Water Relations and Chlorophyll Reading (SPAD) of Sugar Beet Plants under Water Salinity Stress

Generally, irrigation using saline water decreased ($P_{\text{Irrigation}} < 0.0001$) the relative membrane permeability index (RMPI; Figures 2A and S2A), relative water content (RWC; Figures 2B and S2B), and stomatal conductance ($gs$; Figures 2C and S2C), as well as chlorophyll reading (SPAD; Figures 2D and S2D) of beet plants compared to those irrigated with fresh water during the 2019/2020 and 2020/2021 seasons, respectively. Though, these destructive effects were significantly diminished after seed inoculation with PGPR and Si-NP foliar application, or their combination. Briefly, sugar beet plants treated with PGPR+Si-NP had the highest RMPI ($P_{\text{Irrigation} \times \text{Treatment}} < 0.0001$ during both seasons), RWC ($P_{\text{Irrigation} \times \text{Treatment}} < 0.0001$ during both seasons), $gs$ ($P_{\text{Irrigation} \times \text{Treatment}} < 0.0001$ during both seasons), SPAD reading ($P_{\text{Irrigation} \times \text{Treatment}} = 0.0446$ and $P_{\text{Irrigation} \times \text{Treatment}} = 0.0011$ during 2019/2020 and 2020/2021 seasons, respectively). It is worth mentioning that the combined application of PGPR and Si-NP had a better influence on both RMPI, RWC, and $gs$ of beet plants than individual applications which had a greater effect on chlorophyll reading (Figure 2).

![Figure 2](image_url)

**Figure 2.** Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) Relative membrane permeability index (RMPI), (B) relative water content (RWC), (C) stomatal conductance ($gs$), and (D) chlorophyll reading (SPAD) during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test ($P_{\text{Irrigation} \times \text{Treatment}} \leq 0.05$).

2.3. Seed Inoculation with PGPR and Si-NP Foliar Application Advanced the Biochemical Response of Sugar Beet Plants under Water Salinity Stress

Irrigation of beet plants with saline water significantly reduced the leaf content of total soluble sugars (Figures 3A and S3A; $P_{\text{Irrigation}} < 0.0001$) but increased the proline content (Figures 3B and S3B; $P_{\text{Irrigation}} < 0.0001$), in two separate field trials during the 2019/2020 and 2020/2021 seasons. Seed inoculation with PGPR and Si-NP foliar application or their combination significantly increased the leaves content of TSS in beet plants irrigated with fresh water without significant differences between them during 2019/2020. On the other
hand, the application of PGPR, Si-NP, or their combination decreased the proline content in beet leaves under both irrigation conditions ($P_{\text{Irrigation} \times \text{Treatment}} < 0.0001$) during 2019/2020 and 2020/2021, respectively.

![Figure 3](image-url)

**Figure 3.** Effect of seed inoculation with PGPR and/or Si-NP foliar application on the biochemical response of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) Total soluble sugars (TSS; mg g$^{-1}$ DW), and (B) proline content (mg g$^{-1}$ DW) during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test ($P_{\text{Irrigation} \times \text{Treatment}} < 0.05$).

### 2.4. PGPR and Si-NP Application Balanced the Leaf Content of Na$^+$, K$^+$, and Their Ration (K$^+$/Na$^+$) of Sugar Beet Plants under Water Salinity Stress

In general, irrigation of beet plants with saline water in the absence of PGPR and/or Si-NP markedly boosted the Na$^+$ content (Figures 4A and S4A during 2019/2020 and 2020/2021, respectively; $P_{\text{Irrigation} < 0.0001}$) of beet leaves but decreased the K$^+$ content (Figures 4B and S4B during 2019/2020 and 2020/2021, respectively; $P_{\text{Irrigation} < 0.0001}$). As a result of the disruption of Na$^+$ and K$^+$ content, the K$^+$/Na$^+$ profile was also significantly decreased in beet plants irrigated with saline water compared with fresh water-irrigated ones during both seasons (Figures 4C and S4C; $P_{\text{Irrigation} < 0.0001}$). However, the application of PGPR and/or Si-NP considerably manipulated the Na$^+$, K$^+$, and K$^+$/Na$^+$ in the leaves of treated beet plants ($P_{\text{Treatment} < 0.0001}$ for the three parameters in both seasons). Briefly, seed inoculation with PGPR and Si-NP foliar application significantly decreased the Na$^+$ content but increased K$^+$ which resulted in a higher K$^+$/Na$^+$.

### 2.5. Integrated PGPR and Si-NP Application Diminished the Stress Biochemical Indicators in Sugar Beet Plants under Water Salinity Stress

Although irrigation of beet plants using saline water boosted the stress biochemical indicators as expressed by H$_2$O$_2$ content (Figures 5A and S5A; $P_{\text{Irrigation} < 0.0001}$ in both seasons), lipid peroxidation (MDA; Figures 5B and S5B; $P_{\text{Irrigation} < 0.0001}$ in both seasons), and electrolyte leakage (EL; Figures 5C and S5C; $P_{\text{Irrigation} < 0.0001}$ in both seasons), integrated PGPR and Si-NP application notably diminished H$_2$O$_2$, MDA, and EL. Briefly, the application of PGPR, Si-NP, or their combination significantly reduced H$_2$O$_2$ content ($P_{\text{Irrigation} \times \text{Treatment} = 0.0496}$ and 0.0025 in the 2019/2020 and 2020/2021 seasons, respectively) with greater impact by the combined treatment (PGPR+Si-NP). Likewise, integrated PGPR and Si-NP application significantly reduced the lipid peroxidation ($P_{\text{Irrigation} \times \text{Treatment} = 0.0063}$ and 0.0076 in the 2019/2020 and 2020/2021 seasons, respectively), however, no significant differences were noticed in the MDA content between seed inoculation with PGPR and Si-NP foliar application treated plants when irrigated with saline water in the first season (2019/2020) and when plants irrigated with fresh water in the second season (2020/2021).
Figure 4. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) Na⁺ content (mg kg⁻¹ leaf DW), (B) K⁺ content (mg kg⁻¹ leaf DW), and (C) K⁺/Na⁺ ratio during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test (P_{Irrigation × Treatment} ≤ 0.05).

Figure 5. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) H₂O₂ content (µmol g⁻¹ FW), (B) lipid peroxidation
(MDA; nmol g\(^{-1}\) FW), and (C) electrolyte leakage (EL; %) during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test (\(P_{\text{Irrigation} \times \text{Treatment}} \leq 0.05\)).

2.6. PGPR and Si-NP Application Enhanced the Antioxidant-Related Enzymatic Activity in Sugar Beet Plants under Water Salinity Stress

To better understand how PGPR and Si-NP application eases the oxidative stress in saline water-irrigated beet plants, the enzymatic activities of three antioxidant-related enzymes including superoxide dismutase (SOD; Figures 6A and S6A), catalase (CAT; Figures 6B and S6B), and peroxidase (POX; Figures 6C and S6C) were assessed in two separate field trials during the 2019/2020 and 2020/2021 seasons. Generally, in control plants (No PGPR or Si-NP), irrigation of beet plants using saline water significantly decreased the enzymatic activities of all three studied enzymes compared with those in fresh water-irrigated plants (\(P_{\text{Irrigation}} < 0.0001\) for all enzymes in both seasons). However, seed inoculation with PGPR and Si-NP foliar spraying singularly or combined significantly enhanced the activities of all antioxidant enzymes including SOD (\(P_{\text{Irrigation} \times \text{Treatment}} = 0.0147\) and 0.0106), CAT (\(P_{\text{Irrigation} \times \text{Treatment}} = 0.0259\) and 0.0147), and POX (\(P_{\text{Irrigation} \times \text{Treatment}} < 0.0001\)) in the 2019/2020 and 2020/2021 seasons, respectively, with a greater effect of combined treatment (PGPR+Si-NP).

![Figure 6](image_url)

**Figure 6.** Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) Superoxide dismutase (SOD; Unit mg\(^{-1}\) protein), (B) catalase (CAT; Unit mg\(^{-1}\) protein), and (C) peroxidase (POX; Unit mg\(^{-1}\) protein) during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test (\(P_{\text{Irrigation} \times \text{Treatment}} \leq 0.05\)).

2.7. Seed Inoculation with PGPR and Si-NP Foliar Application Enhanced the Yield Traits of Sugar Beet Plants under Water Salinity Stress

Irrigation using saline water negatively altered the yield traits of stressed beet plants including root yield (Figures 7A and S7A; \(P_{\text{Irrigation}} < 0.0001\), foliage yield (Figures 7B and S7B;
2020/2021 seasons, respectively. Similarly, integrated PGPR and Si-NP foliar application significantly boosted all yield traits. Briefly, the dual application of PGPR + Si-NP resulted in the highest root yield (72.93 ± 1.70 and 70.09 ± 1.60 ton ha⁻¹), foliage yield (46.99 ± 1.42 and 45.62 ± 1.19 ton ha⁻¹), total yield (119.92 ± 2.74 and 115.71 ± 2.79 ton ha⁻¹), and sugar yield (13.04 ± 0.32 and 13.80 ± 0.33 ton ha⁻¹) during 2019/2020 and 2020/2021 seasons, respectively. Similarly, integrated PGPR and Si-NP applications to saline water-irrigated beet plants resulted in higher root yield (64.48 ± 0.42 and 62.13 ± 0.39 ton ha⁻¹), foliage yield (41.42 ± 0.31 and 39.67 ± 0.29 ton ha⁻¹), total yield (105.90 ± 0.73 and 101.80 ± 0.68 ton ha⁻¹), and sugar yield (10.83 ± 0.06 and 11.47 ± 0.06 ton ha⁻¹) compared with non-treated stressed plants during 2019/2020 and 2020/2021 seasons, respectively.

Figure 7. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2019/2020 seasons. (A) Root yield (ton ha⁻¹), (B) foliage yield (ton ha⁻¹), (C) total yield (ton ha⁻¹), and (D) sugar yield (ton ha⁻¹) during the 2019/2020 seasons, respectively. Data presented are the means ± standard deviation (mean ± SD) of three biological replicates. Different letters signify statistically significant differences between treatments according to Tukey’s HSD test (P_{Irrigation × Treatment} ≤ 0.05).

3. Discussion

Sugar yield is assessed by the sugar biological yield that relies on the root yield and sugar content, in addition to the content of molasses-forming components (α-amino nitrogen, potassium, and sodium ions) [23]. However, soil salinity and irrigation of plants with saline water are the strongest abiotic stresses that sugar beet crops suffer in arid and semi-arid zones. They detrimentally affect plant physiological responses, sugar yield, and quality through many morph-physiological changes [24]. Accordingly, it is important to implement inexpensive plant nutrition approaches to mitigate soil salinity in lands irrigated with low-quality water in such areas worldwide. We noted that morpho-physiological characteristics and yield were severely diminished in salt-stressed plants irrigated with salt water [25]. Although, when we applied silicon nanoparticles as foliar spray or plant growth-promoting rhizobacteria (PGPR) as seed inoculation, those limiting effects were mitigated; these potential benefits were even more pronounced when applied in combi-
nation compared to untreated plants. Because these combinations make nutrients more available than in untreated plants under salt-affected soil conditions [26].

Retaining higher potassium content at the expense of the soil solution content of sodium in our experiment is the main objective for escaping from soil salinity as well as irrigation with lower quality water and obtaining higher growth of sugar beet plants. The current investigation was performed in a semi-arid area with low precipitation. Soil salinity and irrigation with saline water adversely affected nutrient availability causing an increase in the soil exchangeable sodium percentage (ESP) due to higher Na⁺ ions in the soil solution which causes the phenomenon of antagonism with potassium ions as well as Ca²⁺ and Mg²⁺ ions [27].

The application of PGPR as seed inoculum has the potential to synthesize auxins, primarily indole-3-acetic acid (IAA) which enhances cell elongation and may explain the stimulated plant growth [28]. For example, in our previous studies, P. koreensis MG209738 has been shown to enhance the growth and resilience to salinity stressors of several monocots including rice (Oryza sativa) [29] and maize (Zea mays) [30]. In vitro experiments showed that P. koreensis MG209738 produces IAA in its culture media and actively solubilizes phosphate [29]. Likewise, previously we proved that B. coagulans NCAIM B.01123 can enhance the physiological attributes, and productivity of wheat (Triticum aestivum) grown in salt-affected soil [31]. However, to the best of our knowledge, the effect of the combination of both strains (P. koreensis MG209738 + B. coagulans NCAIM B.01123) on dicot crops, such as sugar beet, has never been investigated previously. It is worth proposing that B. coagulans NCAIM B.01123, being a potential salinity and drought-tolerant PGPR, promoted sugar beet growth due to its 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity that could decrease ethylene concentration in the stressed roots [32]. Microbial ACC-deaminase activity is associated with the biosynthesis and signaling of phytohormone ethylene by preventing the conversion of ACC into ethylene, which enhances the water-holding capacity and alleviates the harmful impact of salinity on roots [33]. We believe that seed inoculation with a mixture of P. koreensis MG209738 and B. coagulans NCAIM B.01123 may affect the phytohormonal balance within the treated plants. However, further studies are required to better understand the potential effect(s) of both strains on the phytohormonal profile of treated plants.

Moreover, foliar spraying of silica nanoparticles (Si-NP) can also stimulate the biosynthesis of plant hormones, and maintain physiological processes by alleviating oxidative damage by SODs, which mitigate salt stress [34]. It was also observed that the growth of sugar beet was maximized such as leaf area per plant with the combined use of PGPR and silicon nanoparticles that secrete polysaccharides from soil microbes that increased organic molecules in the atmospheric roots resulting in a reduction of Na⁺ ions and increased leaf area per plant, which improved soil physiochemical properties [35]. Based on the above-mentioned, it was also found that nutrient uptake and their content in the leaves increased, such as increased levels of potassium and a decrease in the content of sodium ions, which may indicate the secretion of IAA and exopolysaccharides under soil salinity in sugar beet plants subjected to irrigation with saline water [36]. So, the coupled impact of PGPR and Si-NP can increase K⁺ flux and decrease Na⁺ flux in sugar beet plants under irrigation with saline water in soil salinity. A similar finding has been described by [37].

The beneficial impact of PGPR and Si-NP on growth under salt-affected soil increase chlorophyll biosynthesis, stomatal conductance, relative water content as well as relative membrane permeability and total soluble sugars, thus stimulating the higher activities of photosynthesis and meristematic activity increasing cell division and enlargement [38]. Moreover, the heightened SPAD chlorophyll by Si-NP could also be ascribed to its potential to be an activator of many enzymes (especially SOD, CAT, and POX) involved in the detoxification of ROS (MDA and H₂O₂) produced under soil salinity and irrigation with saline water [39]. In addition, PGPR has the potential to solubilize inorganic forms and make them easy to uptake by plant roots in addition to activating soil microbes that
improves soil fertility, especially the soil’s physical and chemical characteristics resulting in increased root yield [40].

Accumulation of proline and increased electrolyte leakage were found in saline-irrigated sugar beet plants growing in saline-affected soils. However, the application of PGPR coupled with Si-NP reduced the proline content and electrolyte leakage produced under these abiotic stresses [41]. It has been proven that seed inoculation with PGPR is capable to produce phytohormones, resulting in boosting the foliage and root yield due to reducing the proline content and electrolyte leakage [42]. Si-NP applied to the leaves remarkably compensated for proline and electrolyte leakage by directing the plant to synthesize more soluble sugars to ensure osmotic modifications and maintain plant growth [42]. Moreover, the application of PGPR along with Si-NP contains many essential nutrients which are released during their breakdown that increase the activity of antioxidant enzymes and reduces oxidative stress resulting in improved plant metabolism, reducing proline accumulation, and reducing electrolyte leakage in addition to its impact as a bio-stimulant in protecting plant cells [43].

PGPR application along with Si-NP could enhance vegetative growth including leaf area and phenotypic characteristics such as root length and root diameter through augmented cell division and enlargement due to increased nutrient and water uptake causing observed improvement in sugar beet quality characteristics and root yield along with sugar content under environmental stressors [44]. PGPR application combined with Si-NP could improve plant metabolism by synthesis of phytohormones, organic acid, phosphatases, IAA, gibberellins, and minerals and synthesis of auxins and ACC deaminase which ultimately enhance plant growth and crop yield [45].

The sugar yield is the result of the sucrose content in the juice extracted from the roots of the sugar beet. Nevertheless, the presence of impurities, i.e., Na+, K+, and α-amino nitrogen, in high amounts in beet juice has a detrimental molasses impact that declines the sugar produced from the beet pulp and therefore sugar production [46]. Si-NP combined with PGPR have maximized sugar yield, while the non-sugar components (Na+, K+, and α-amino nitrogen) were reduced under saline water irrigation conditions in saline-affected soils. These data agree with [47]. The positive impact of PGPR-conjugated Si-NP on sugar quality may be attributed to the increased uptake of potassium and silicon and decreasing the influx of Na+ ions into root cells as in our investigation, which has an important role in transporting photosynthetics (e.g., sucrose) from leaves to accumulate in storage root cells [48]. An additional possible reason for the decrease of K and α-amino nitrogen in beet juice is that K and α-amino nitrogen are the predominant osmotic metabolites through the vegetative phase under salinity [49]. Nevertheless, once the soluble sugars are in storage, these osmolytes correspondingly decrease in the storage root cells because it is compensated by the soluble sugars [50]. The increase in quality and sugar ratios due to the application of PGPR to the seeds coupled with Si-NP to the leaves can be ascribed to its role in reducing impurity materials like α-amino nitrogen, Na, and K and increasing the purity of the juice [51].

4. Materials and Methods
4.1. Experimental Design, Treatments, and Sampling

Two field trials were implemented in the experimental farm of Elamaar village in Sidi Salem zone, Governorate of Kafr El-Sheikh (31° 21’ 9” N, 30° 50’ 27” E), Egypt to estimate the effect of plant growth promoting rhizobacteria (two bacterial strains of *P. koreensis* and *B. coagulans*) and foliar spraying with silica nanoparticles (Si-NP) as singularly and/or coupled under two irrigation treatments (irrigation with saline water and irrigation with fresh water) on growth and productivity of sugar beet plants (*Beta vulgaris* L. var. Poly Oscar; 10 kg seeds ha⁻¹) grown in saline soil. Sugar beet seeds which were attained from Sugar Crops Research Institute, Agricultural Research Center, Giza, Egypt, were planted on 12 September 2019/2020 and repeated on 15 September 2020/2021 growing seasons. Seeds were planted mechanically at a rate of 2 to 3 balls per hill and then were thinned to
keep 1 plant per hill pre the next irrigation. The chemical attributes of physicochemical properties of soil samples at a depth of 0–30 cm from the experimental site are shown in Table 1, whereas the chemical attributes of irrigation water from the experimental site are shown in Table 2.

Table 1. Analysis of soil physicochemical properties during the 2019/2020 and 2020/2021 seasons.

| Season     | OM (%) | Soil Texture | EC (dS m⁻¹) | FC (%) | pH | Cations (mmol L⁻¹) | Anions (mmol L⁻¹) |
|------------|--------|--------------|-------------|--------|----|-------------------|-------------------|
|            |        |              | Na⁺         | K⁺     | Mg²⁺ | Ca²⁺ | Cl⁻ | HCO₃⁻ | SO₄²⁻ |
| 2019/2020  | 1.45   | Clay loam    | 6.88        | 28.75  | 8.22 | 16.74 | 9.36 | 6.18  | 9.31  |
| 2020/2021  | 1.39   | Clay loam    | 6.76        | 29.36  | 8.17 | 17.63 | 9.36 | 8.63  | 8.67  |

OM: organic matter; EC: electric conductivity; FC: field capacity.

Table 2. Characterization of irrigation water during the 2019/2020 and 2020/2021 growing seasons.

| Character | Freshwater * | Saline Water |
|-----------|--------------|--------------|
|           | 2019/2020    | 2020/2021    | 2019/2020    | 2020/2021    |
| pH        | 7.65 ± 0.74  | 7.22 ± 0.71  | 6.25 ± 0.12  | 6.14 ± 0.10  |
| EC (dS m⁻¹) | 0.65 ± 0.14  | 0.63 ± 0.02  | 5.84 ± 0.08  | 5.65 ± 0.11  |
| SAR       | 1.58 ± 0.13  | 1.35 ± 0.04  | 7.88 ± 0.14  | 7.47 ± 0.12  |
| Na⁺ (mmol L⁻¹) | 1.75 ± 0.12  | 1.87 ± 0.03  | 16.22 ± 1.35 | 16.58 ± 1.21 |
| Cl⁻ (mmol L⁻¹) | 3.63 ± 0.13  | 3.54 ± 0.04  | 11.55 ± 0.75 | 11.69 ± 0.02 |
| SO₄²⁻ (mmol L⁻¹) | 0.22 ± 0.02  | 0.11 ± 0.01  | 3.87 ± 0.41  | 4.18 ± 0.11  |
| NH₄⁺ (mmol L⁻¹) | 1.63 ± 0.04  | 1.74 ± 0.02  | 2.65 ± 0.03  | 2.25 ± 0.04  |
| COD (mg L⁻¹)   | 12.12 ± 0.85 | 11.12 ± 1.12 | ND           | ND           |
| BOD (mg L⁻¹)   | 5.63 ± 0.27  | 5.24 ± 0.23  | ND           | ND           |
| SS (mg L⁻¹)    | 199 ± 12.42  | 172 ± 13.45  | 19 ± 1.5     | 17 ± 1.6     |
| DS (mg L⁻¹)    | 299 ± 27     | 388 ± 25     | 1789 ± 118   | 1855 ± 117   |

COD: chemical oxygen demand; BOD: biological oxygen demand; SS: suspended solids; DS: dissolved solids; ND: not detected. * Well water at a depth of 20 m.

The experimental layout was a strip plot with four replications per treatment. The main plots were assigned to two irrigation (fresh water vs. saline water) treatments (6 × 16 m each with a total area of 96 m²). The sub-plots (4 × 6 m each) were distributed for the treatments of seed inoculation with plant growth-promoting rhizobacteria (PGPR), foliar spray with Si-NP, their combination (PGPR+ Si-NP), and untreated plots (control). Each sub-plot (24 m²) included 7 ridges, that were 50 cm wide and 6 m long, with 20 cm apart between hills. In other words, each biological replicate contained approximately 56 independent plants. For sampling, five leaves were collected randomly at 80 days post-sowing (DPS) from each replicate (4 replicates per treatment). Collected leaves were chopped, mixed together, processed directly, or kept at −80 °C for further analyses.

For PGPR treatment, two PGPR strains (Pseudomonas koreensis MG209738 and Bacillus coagulans NCAIM B.01123) were obtained from the Department of Agricultural Microbiology, Soils, Water and Environment Research Institute (SWERI), Agricultural Research Centre (ARC), Egypt. Briefly, 150 mL of 1 × 10⁸ CFU mL⁻¹ from each culture per 250 g carrier and homogenously with sugar beet seeds pre-planting (final concentration 950 g ha⁻¹). For Si-NP treatment, plants were foliar-sprayed twice with Si-NP (12.5 mg L⁻¹) at 45 and 60 DPS. Si-NP spraying was attained by the Agricultural Microbiology Department, Sakha Agricultural Research Station, Kafr El-Sheikh, Egypt. The attributes of Si-NP (SiO₂) were 260–320 m² g⁻¹ for specific surface area, 4–4.5 for pH, and 10 nm for diameter. Weeds were eliminated by up-rooting from the field three times through the crop growth stages. NPK fertilization was done using 200, 180, and 120 kg ha⁻¹, respectively, as ammonium nitrate (33.5% N), Ca-superphosphate (15.5% P₂O₅), and K-sulfate (48% K₂O).
4.2. Leaf Area per Plant (dm$^2$)

Five plants were selected from the middle of each replicate at 80 days from sowing to measure leaf area according to Watson [52] using leaf area meter (LA-3000A, LI-COR Inc., Lincoln, NE, USA).

4.3. Inorganic Solutes

Five samples of leaves were detached at 80 days after sowing from each treatment, rinsed with distilled water, and dried for 72 h at 70 °C. Then finely ground plant samples were treated with HNO$_3$: HClO$_4$ (2:1 v/v) for 120 min at 220 °C. Leaf sodium content (Na$^+$; mg kg$^{-1}$ dry weight [DW]) and potassium content (K$^+$; mg kg$^{-1}$ DW) were determined using the atomic absorption flame spectrophotometer (Model AA-6400 F, Shimadzu Corporation, Nakagyo-ku, Kyoto, Japan) based on the method of Thomas [53].

4.4. Physiological Measurements

4.4.1. Chlorophyll Reading (SPAD)

Leaf samples were collected as described above to determine chlorophyll content by a SPAD meter (Model: SPAD-502, Konica Minolta, Chiyoda-ku, Tokyo, Japan), in the top expanded leaf as explained by Ling et al. [54].

4.4.2. Stomatal Conductance ($g_s$)

Stomatal conductance (mmol H$_2$O m$^{-2}$ s$^{-1}$) was determined using a dynamic diffusion porometer (Delta-T AP4, Delta-T Devices Ltd., Cambridge, UK). Total leaf conductance ($r_l$) is $1/r_l = 1/r_a + 1/r_b$; where the front ($r_a$) and backside ($r_b$) of the center of the leaf.

4.4.3. Relative Water Content (RWC)

Collected leaves, as described above, were directly weighed to measure the fresh weight (FW). Then samples were kept in distilled water for 24 h then weighed again to assess the leaf’s turgid weight (TW). Eventually, samples were dried at 70 °C for 72 h to assess the dry weight (DW). Then, the leaf’s relative water content was calculated using the method of Weatherley [55] using Equation (1):

$$ RWC = \left(\frac{FW - DW}{TW - DW}\right) \times 100 \quad (1) $$

4.4.4. Relative Membrane Permeability Index (RMPI)

Relative membrane permeability index (RMPI) was assessed as explained by Yang et al. [56] which was measured by a conductivity meter (TC-OMEGA, USA). Ten discs of leaves were put in test tubes including 20 mL of deionized water. The initial electrical conductivity (EC$_0$) of each treatment was estimated by placing it in vortexes for five seconds. Then, the electrical conductivity (EC$_1$) was measured again by placing the test tubes at 4 °C for a day. Finally, the electrical conductivity (EC$_2$) was measured again by autoclaving at 120 °C for 20 min. Then, RMPI was computed using Equation (2):

$$ RMPI = 1 - \left(\frac{EC_1 - EC_0}{EC_2 - EC_0}\right) \times 100 \quad (2) $$

4.5. Oxidative Stress Indicators

4.5.1. Hydrogen Peroxide (H$_2$O$_2$) Content

Approximately 500 mg of leaf samples were ground to a fine powder using liquid nitrogen and used to colorimetrically assess hydrogen peroxide (H$_2$O$_2$) after extraction with trichloroacetic acid (TCA: 0.1%) at 3000 rpm for 20 min. using method of Velikova, et al. [57]. H$_2$O$_2$ contents were assessed as µmol g$^{-1}$ FW.
4.5.2. Lipid Peroxidation

Lipid peroxidation (MDA) was determined using 500 mg of ground leaf samples after homogenously extracted in 0.01% butyl hydroxyl toluene (BHT) and brewed at 95 °C. Thiobarbituric acid reactive substances (TBARS) were assessed according to Du and Bramlage [58]. Then, the extraction was subjected to centrifugation at 10,000 × g for 15 min and assessed spectrophotometrically at 532 and 600 nm computed in nmol g⁻¹ FW.

4.5.3. Antioxidant Enzymes

About 500 mg ground leaf samples were used to assess the enzymatic activities of superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX), after extraction in 5 mL of cold 100 mM K-phosphate buffer (pH 7, containing 0.5 g insoluble PVP, 0.1 mM EDTA and 2 mL L⁻¹ Triton X-100), and centrifuging them for 15 min at 11,000 × g at 4 °C. The activity of SOD (EC 1.15.1.1) was calculated by estimating the enzyme to produce 50% inhibition of the reduction of cytochrome c by superoxide caused by xanthine oxidase generated according to Beauchamp and Fridovich [59]. The specific activity of SOD is expressed as Unit mg⁻¹ protein. Catalase (EC 1.11.1.6) activity was assessed by Aebi [60], and the absorbance was measured at 240 nm of a reaction mixture containing 1.9 mL H₂O₂, 1.0 mL of 5.9 mM H₂O₂ in potassium phosphate buffer (pH 7.0), and 1.0 mL extract. The specific activity of CAT is expressed as Unit mg⁻¹ protein. Peroxidase (EC 1.11.1.7) activity was assessed by the method of Vetter et al. [61] combining 100 µL enzyme extract with 2.9 mL 50 mM phosphate-citrate buffer (pH 6.5), 0.03% H₂O₂. At 430 nm, the change in absorbance was calculated for 5 min. The specific activity of POX is computed as Unit mg⁻¹ protein.

4.6. Osmolytes Determination

4.6.1. Electrolyte Leakage

Electrolyte leakage was assessed based on the technique of Naghashzadeh et al. [62]. Five samples of leaves (0.5 g) were selected randomly at 80 days after sowing from each treatment and were introduced into 10 mL distilled water and electrical conductivity (EC1) was computed after 12 h (A) by conductivity meter. Samples were later autoclaved for 15 min at 80 °C to assess electrical conductivity (C2). The electrolyte leakage was measured using Equation (3).

\[ EL = \left( \frac{C1}{C2} \right) \times 100 \]  

(3)

4.6.2. Proline Content

Proline was extracted from 500 mg freeze-dried powdered samples with 3% sulfosalicylic acid and determined using the technique of Bates et al. [63]. Proline was calculated by the standard curve and computed in mg g⁻¹ DW.

4.6.3. Total Soluble Sugars (TSS)

Total soluble sugar was determined using the anthrone method as described by Sadasivam and Manickam [64]. Briefly, TSS was extracted with 80% ethanol (v/v) at 80 °C. The total soluble sugars were calculated by the glucose standard curve and stated as mg g⁻¹ DW.

4.7. Morphology and Yield Measurements

4.7.1. Root Length and Diameter

At the harvest time (at 177 days), five plants were selected randomly to assess root length (cm) which was computed by meter-scale from the point where the top was removed to the bottom of the root. Root diameter (cm) was assessed by the vernier caliper at the widest part of the root.
4.7.2. Sugar Beet Yield

At the harvest time (at 177 days), five plants were selected randomly to assess foliage yield (ton ha\(^{-1}\)), root yield (ton ha\(^{-1}\)), and sugar yield (ton ha\(^{-1}\)) in addition to sugar %. Roots and tops were detached individually, rinsed, and weighed to assess foliage yield (ton ha\(^{-1}\)), and root yield (ton ha\(^{-1}\)). Sugar content (%) was assessed by Saccharometer on a lead basis using the technique of Delta sugar company by AOAC method A.O.A.C [65]. Sugar yield (ton ha\(^{-1}\)) = root yield (ton ha\(^{-1}\)) × Sugar content (%).

4.8. Statistical Analysis

The analysis of variance (ANOVA) was used to test the significant differences among irrigation regimes (\(P_{\text{Irrigation}}\)), treatments (\(P_{\text{Treatment}}\)), and their interaction (\(P_{\text{Irrigation} \times \text{Treatment}}\)). Tukey’s honestly significant difference (HSD) test was used for post-hoc analysis based on the \(p\)-value of the interaction between irrigation regimes and treatments (\(P_{\text{Irrigation} \times \text{Treatment}} < 0.05\)).

5. Conclusions

Previously, several plant growth-promoting rhizobacteria (PGPR) were isolated and characterized from numerous plant species such as tomato [66], as well as endophytes and PGPR were used in the biosynthesis of nanoparticles [67]. However, our knowledge about the potential role(s) of PGPR and Si-NP in stimulating sugar beet resilience to salinity stress (water or soil) was limited. Our findings from this study showed that the exposure of sugar beet plants to high soil salinity and irrigated with saline water simultaneously increase the osmotic stress, which augments the oxidative damage, weakens the selectivity, and diminishes the morpho-physiological characteristics. The attained findings displayed that the coupled use of PGPR and Si-NP positively lessened the detrimental impact of co-stressors (soil salinity and irrigation with saline water) in addition to enhanced morpho-physiological characteristics, productivity, and sugar beet quality. Future examinations are expected to affirm the attained findings on a large scale. Nevertheless, further studies are required to better understand the molecular and biochemical mechanisms behind how PGPR and/or Si-NP stimulate the plant response against abiotic stress.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/plants11223117/s1. Figure S1. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the growth of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 season. Figure S2. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons. Figure S3. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the biochemical response of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons. Figure S4. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons. Figure S5. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons. Figure S6. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons. Figure S7. Effect of seed inoculation with PGPR and/or Si-NP foliar application on the water relations and chlorophyll reading of sugar beet plants grown in salt-affected soil and subjected to saline water irrigation during the 2020/2021 seasons.

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References

1. Stevanato, P.; Biaggi, M.D.; Skaracis, G.N.; Colombo, M.; Mandolino, G.; Biancardi, E. The sea beet (Beta vulgaris L. ssp. maritima) of the Adriatic coast as source of resistance for sugar beet. Sugar Tech 2001, 3, 77–82. [CrossRef]
2. Ministry of Agriculture and Land Reclamation. Sugar Crops and Sugar Production in Egypt and the World; MALR Annual Report; Council of Sugar Crops: Giza, Egypt, 2019.
3. Abd El-Mageed, T.A.; Rady, M.O.A.; Semida, W.M.; Shaaban, A.; Mekdad, A.A.A. Exogenous micronutrients modulate morphophysiological attributes, yield, and sugar quality in two salt-stressed sugar beet cultivars. J. Soil Sci. Plant Nutr. 2021, 21, 1421–1436. [CrossRef]
4. Leilah, A.A.A.; Khan, N. Interactive Effects of Gibberellic Acid and Nitrogen Fertilization on the Growth, Yield, and Quality of Sugar Beet. Agronomy 2021, 11, 137. [CrossRef]
5. Artyszak, A.; Gozdowski, D.; Siuda, A. Effect of the Application Date of Fertilizer Containing Silicon and Potassium on the Yield and Technological Quality of Sugar Beet Roots. Plants 2021, 10, 370. [CrossRef] [PubMed]
6. Khan, M.A.; Tahir, A.; Khurshid, N.; Husnain, M.I.; Ahmed, M.; Boughanmi, H. Economic effects of climate change-induced loss of agricultural production by 2050: A case study of Pakistan. Sustainability 2020, 12, 1216. [CrossRef]
7. Kheir, A.M.S.; Abouelsoud, H.M.; Hafez, E.M.; Ali, O.A.M. Integrated effect of nano-Zn, nano-Si, and drainage using crop straw–filled ditches on saline sodic soil properties and rice productivity. Arab. J. Geosci. 2019, 12, 471. [CrossRef]
8. Hafez, E.M.; Osman, H.S.; Gowayed, S.M.; Okasha, S.A.; Omara, A.E.-D.; Sami, R.; Abd El-Monem, A.M.; Abd El-Razek, U.A. 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 2021, 11, 676. [CrossRef]
9. Lv, X.; Chen, S.; Wang, Y. Advances in understanding the physiological and molecular responses of sugar beet to salt stress. Front. Plant Sci. 2019, 10, 1431.
10. Munns, R. Comparative physiology of salt and water stress. Plant Cell Environ. 2002, 25, 239–250. [CrossRef]
11. Aliya, F.; Asghari, B. Role of Plant Growth-Promoting Rhizobacteria (PGPR), Biochar, and Chemical Fertilizer under Salinity Stress. Commun. Soil Sci. Plant Anal. 2016, 47, 1985–1993.
12. Ahmad, M.T.; Asghar, H.N.; Saleem, M.; Khan, M.Y.; Zahir, Z.A. Synergistic effect of rhizobia and biochar on growth and physiology of maize. Agron. J. 2015, 107, 2327–2334. [CrossRef]
13. Baig, K.S.; Arshad, M.; Khalid, A.; Hussain, S.; Abbas, M.N.; Imran, M. Improving growth and yield of maize through bioinoculants carrying auxin production and phosphate solubilizing activity. Soil Environ. 2014, 33, 159–168.
14. Chandra, D.; Srivastava, R.; Glick, B.R.; Sharma, A.A. Drought-Tolerant Pseudomonas spp. Improve the Growth Performance of Finger Millet (Eleusine coracana (L.) Gaertn.) Under Non-Stressed and Drought-Stressed Conditions. Pedosphere 2018, 28, 227–240. [CrossRef]
15. Ngumbi, E.; Kloeper, J. Bacteria-mediated drought tolerance: Current and future prospects. Appl. Soil Ecol. 2016, 105, 109–125.
16. Ayuso-Calles, M.; Flores-Félix, J.D.; Rivas, R. Overview of the role of rhizobacteria in plant salt stress tolerance. Agronomy 2021, 11, 1759. [CrossRef]
17. Yang, A.; Akhtar, S.S.; Iqbal, S.; Amjad, M.; Naveed, M.; Zahir, Z.A.; Jacobsen, S.E. Enhancing salt tolerance in quinoa by halotolerant bacterial inoculation. Funct. Plant Biol. 2016, 43, 632–642.
18. Liu, R.; Lal, R. Potentials of engineered nanoparticles as fertilizers for increasing agronomic productions. *Sci. Total Environ.* 2015, 514, 131–139. [CrossRef]

19. Hafez, E.M.; Gowayed, S.M.; Nehela, Y.; Sakran, R.M.; Rady, A.M.S.; Awadalla, A.; Omara, A.E.D.; Alowaiesh, B.F. Incorporated Biochar-Based Soil Amendment and Exogenous Glycine Betaine Foliar Application Ameliorate Rice (*Oryza Sativa L.*) Tolerance and Resilience to Osmotic Stress. *Plants* 2021, 10, 1930. [CrossRef]

20. Ding, Z.; Kheir, A.M.S.; Ali, O.A.M.; Hafez, E.M.; ElShamey, E.A.; Zhou, Z.; Wang, B.; Lin, X.; Ge, Y.; Fahmy, A.E.; et al. A vermicompost and deep tillage system to improve saline-sodic soil quality and wheat productivity. *J. Environ. Manag.* 2021, 277, 11388. [CrossRef]

21. Hafez, E.M.; Omara, A.E.D.; Hafez, E.M.; Osman, H.S.; Rashwan, E.; El-Said, M.A.A.; Alharbi, K.; Abd El-Moneim, D.; Gowayed, S.M. Foliar-applied potassium silicate coupled with plant growth-promoting rhizobacteria improves growth, physiology, nutrient uptake and productivity of faba bean (*Vicia faba L.*) irrigated with saline water in salt-affected soil. *Plants* 2021, 10, 894. [CrossRef]

22. Seleiman, M.F.; Hafez, E.M. Optimizing Inputs Management for Sustainable Agricultural Development. In *Mitigating Environmental Stresses for Agricultural Sustainability in Egypt*; Awaad, H., Abu-hashim, M., Negm, A., Eds.; Springer: Cham, Switzerland, 2021. [CrossRef]

23. Artyszak, A. *Agronomic and Habitat Conditions for Sugar Beet Yielding and Health*; Treatises and Monographs, 398; Warsaw University of Life Sciences Press: Warsaw, Poland, 2012. p. 154.

24. Osman, H.S.; Rady, A.M.S.; Awadalla, A.; Omara, A.E.-D.; Hafez, E.M. 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.* 2021, 16, 119–135. [CrossRef]

25. Abdelrasheed, K.G.; Mazrou, Y.; Omara, A.E.D.; Osman, H.S.; Nehela, Y.; Hafez, E.M.; Rady, A.M.S.; El-Moneim, D.A.; Alowaiesh, B.F.; Gowayed, S.M. Soil Amendment Using Biochar and Application of K-Humate Enhance the Growth, Productivity, and Nutritional Value of Onion (*Allium Cepa L.*) under Deficit Irrigation Conditions. *Plants* 2021, 10, 2598. [CrossRef] [PubMed]

26. Alharbi, K.; Rashwan, E.; Mohamed, H.H.; Awadalla, A.; Omara, A.E.-D.; Hafez, E.M.; Alshaal, T. Application of Silica Nanoparticles in Combination with Two Bacterial Strains Improves the Growth, Antioxidant Capacity and Production of Barney Irrigated with Saline Water in Salt-Affected Soil. *Plants* 2022, 11, 2026. [CrossRef] [PubMed]

27. Sposito, G.; LeVesque, C.S. Sodium-Calcium-Magnesium Exchange on Silver Hill Illite. *Sodium-Calcium-Magnesium Exchange on Silver Hill Illite.* *Soil Sci. Total Environ.* 1989, 49, 1153–1159. [CrossRef]

28. Danish, S.; Zafar-ul-Hye, M.; Hussain, S.; Riaz, M.; Qayyum, M. Mitigation of drought stress in maize through inoculation with drought tolerant ACC deaminase containing PGPR under axenic conditions. *Pak. J. Bot.* 2020, 52, 49–60. [CrossRef]

29. Hafez, E.M.; Alsohim, A.S.; Farig, M.; Omara, A.E.D.; Rashwan, E.; Kamara, M.M. Synergistic Effect of Biochar and Plant Growth Promoting Rhizobacteria on Alleviation of Water Deficit in Rice Plants under Salt-Affected Soil. *Agronomy* 2019, 9, 847. [CrossRef]

30. Nehela, Y.; Mazrou, Y.S.A.; Alshaal, T.; Rady, A.M.S.; El-Sherif, A.M.A.; Omara, A.E.D.; El-Moneim, A.M.A.; Hafez, E.M. The Integrated Amendment of Sodic-Saline Soils Using Biochar and Plant Growth-Promoting Rhizobacteria EnhancesMaize (*Zea Mays L.*) Resilience to Water Salinity. *Plants* 2021, 10, 1960. [CrossRef]

31. Omara, A.E.D.; Hafez, E.M.; Osman, H.S.; Rashwan, E.; El-Said, M.A.A.; Alharbi, K.; Abd El-Moneim, D.; Gowayed, S.M. Collaborative Impact of Compost and Beneficial Rhizobacteria on Soil Properties, Physiological Attributes, and Productivity of Wheat Subjected to Deficit Irrigation in Salt Affected Soil. *Plants* 2022, 11, 877. [CrossRef]

32. Ilangumaran, G.; Smith, D.L. Plant Growth Promoting Rhizobacteria in Amelioration of Salinity Stress: A Systems Biology Perspective. *Front. Plant Sci.* 2017, 8, 1768. [CrossRef]

33. Nehela, Y.; Killiny, N. The Unknown Soldier in Citrus Plants: Polymaines-Based Defensive Mechanisms against Biotic and Abiotic Stresses and Their Relationship with Other Stress-Associated Metabolites. *Plant Signal. Behav.* 2020, 15, e1761080-2. [CrossRef]

34. Esmaili, S.; Tavallali, V.; Amiri, B. Nano-Silicon Complexes Enhance Growth, Yield, Water Relations and Mineral Composition in Tanacetum parthenium under Water Deficit Stress. *Silicon* 2013, 13, 2493–2508. [CrossRef]

35. Fugate, K.K.; Lafta, A.M.; Eide, J.D.; Li, G.; Lulai, E.C.; Olson, L.L.; Deckard, E.L.; Khan, M.F.R.; Finger, F.L. Methyl jasmonate alleviates drought stress in young sugar beet (*Beta vulgaris L.*) plants. *J. Agron. Crop Sci.* 2018, 204, 566–576. [CrossRef]

36. Benjelloun, I.; Thami Alami, I.; El Khadir, M.; Douira, A.; Udupa, S.M. Co-Inoculation of Mesorhizobium ciceri with Either Bacillus sp. or Enterobacter aerogenes on Chickpea Improves Growth and Productivity in Phosphate-Deficient Soils in Dry Areas of a Mediterranean Region. *Plants* 2021, 10, 571. [CrossRef] [PubMed]

37. Rizwan, M.; Ali, S.; Ibrahim, M.; Farid, M.; Adrees, M.; Bharwana, S.A.; Zia-ur-Rehman, M.; Qayyum, M.F.; Abbas, F. Mechanisms of silicon-mediated alleviation of drought and salt stress in plants: A review. *Environ. Sci. Pollut. Res.* 2015, 22, 15416–15431. [CrossRef]

38. Kalteh, M.; Alipour, Z.T.; Ashraf, S.; Marashi, A.M.; Falah, N.A. Effect of silica nanoparticles on basil (*Ocimum basilicum*) under salinity stress. *J. Chem. Health Risks* 2018, 4, 49–55.

39. El-Shamy, M.A.; Alshaal, T.; Mohamed, H.H.; Rady, A.M.; Hafez, E.M.; Alsohim, A.S.; Abd El-Moneim, D. Quinoa Response to Application of Phosphogypsum and Plant Growth-Promoting Rhizobacteria under Water Stress Associated with Salt-Affected Soil. *Plants* 2022, 11, 872. [CrossRef]

40. Bhanse, P.; Kumar, M.; Singh, L.; Awasthi, M.K.; Qureshi, A. Role of plant growth-promoting rhizobacteria in boosting the phytoremediation of stressed soils: Opportunities, challenges, and prospects. *Chemosphere* 2020, 303, 134954. [CrossRef]
41. Zarski, J.; Kuśmierek-Tomaszewska, R.; Dudek, S. Impact of irrigation and fertilization on the yield and quality of sugar beet (Beta vulgaris L.) in a moderate climate. *Agronomy* 2020, 10, 166. [CrossRef]

42. Farhaoui, A.; Adadi, A.; Tahiri, A.; Alami, N.E.; Khayi, S.; Mentag, R.; Ezrari, S.; Radouane, N.; Mokrini, F.; Belabess, Z.; et al. Biocontrol potential of plant growth-promoting rhizobacteria (PGPR) against *Sclerotiorum rolfsii* diseases on sugar beet (Beta vulgaris L.). *Physio. Mol. Plant Pathol.* 2022, 119, 101829. [CrossRef]

43. Namjoo, S.; Sorooshzadeh, A.; Rajabi, A.; AghaaliKhani, M. Nano-silicon protects sugar beet plants against water deficit stress by improving the antioxidant systems and compatible solutes. *Acta Physiol. Plant.* 2020, 42, 157. [CrossRef]

44. Farooq, M.A.; Saqib, Z.A.; Akhtar, J.; Bakhit, H.E.; Pasala, R.-K.; Dietz, K.-J. Protective role of silicon (Si) against combined stress of salinity and boron (B) toxicity by improving antioxidant enzymes activity in rice. *Silicon* 2015, 11, 2193–2197. [CrossRef]

45. Mekdad, A.A.A.; Rady, M.M. Response of Beta vulgaris L. to nitrogen and micronutrients in dry environment. *Plant Soil Environ.* 2016, 62, 23–29. [CrossRef]

46. Zewail, R.M.Y.; El-Gmal, I.S.; Khaitov, B.; El-Desouky, H.S. Micronutrients through foliar application enhance growth, yield and quality of sugar beet (Beta vulgaris L.). *J. Plant Nut.* 2020, 43, 2275–2285. [CrossRef]

47. Dutton, J.; Huijbregts, T. Root quality and processing. In *Sugar Beet*; Draycott, A.P., Ed.; Blackwell Publishing: Oxford, UK, 2006; pp. 409–442. [CrossRef]

48. Jafarzadeh, A.A.; Aliasgharzad, N. Salinity and salt composition effects on seed germination and root length of four sugar beet cultivars. *Biologia* 2007, 62, 562–564. [CrossRef]

49. Geng, G.; Lv, C.; Stevanato, P.; Li, R.; Liu, H.; Yu, L.; Wang, Y. Transcriptome analysis of salt-sensitive and tolerant genotypes reveals salt-tolerance metabolic pathways in sugar beet. *Int. J. Mol. Sci.* 2019, 20, 5910. [CrossRef]

50. Dadkhah, A.; Moghtader, H. Sugar beet plant–water uptake and plant–water relationships under saline growth conditions. *Comp. Biochem. Physiol. Phys.* 2007, 146, S275–S276.

51. Ghoulam, C.; Foursy, A.; Fares, K. Effects of salt stress on growth, inorganic ions and proline accumulation in relation to osmotic adjustment in five sugar beet cultivars. *Environ. Exp. Bot.* 2002, 47, 39–50. [CrossRef]

52. Watson, D.J. The dependence of net assimilation rate on leaf area index. *Ann. Bot. Lond.* 1958, 22, 37–54.

53. Thomas, G.W. *Methods of Soil Analysis. Part 3. Chemical Methods*; Soil Science Society of America: Madison, WI, USA, 1996; pp. 475–490, ISBN 9780891188667.

54. Ling, Q.; Huang, W.; Jarvis, P. Use of a SPAD-502 meter to measure leaf chlorophyll concentration in *Arabidopsis thaliana*. *Photosynth. Res.* 2010, 107, 209–214. [CrossRef]

55. Weatherley, P.E. Studies in water relations of cotton plants. The field measurement of water deficit in leaves. *New Phytol.* 1950, 49, 81–87. [CrossRef]

56. Yang, Y.; Guo, Y. Elucidating the molecular mechanisms mediating plant salt-stress responses. *New Phytol.* 2018, 217, 523–539. [CrossRef] [PubMed]

57. Velikova, V.; Yordanov, I.; Edreva, A. Oxidative stress and some antioxidant systems in acid rain-treated bean plants: Protective role of exogenous polyamines. *Plant Sci.* 2000, 151, 59–66. [CrossRef]

58. Du, Z.; Bramlage, W.J. Modified thiobarbituric acid assay for measuring lipid oxidation in sugar-rich plant tissue extracts. *J. Agric. Food Chem.* 1992, 40, 1566–1570. [CrossRef]

59. Beauchamp, C.; Fridovich, I. Superoxide dismutase: Improved assays and an assay applicable to acrylamide gels. *Anal. Biochem.* 1971, 44, 276–287. [CrossRef]

60. Aebi, H. Catalase in vitro. In *Methods in Enzymology*; Draycott, A.P., Ed.; Blackwell Publishing: Oxford, UK, 2006; pp. 5910. [CrossRef]

61. Aoji, H. Catalytic Potential of Endophytes Facilitates Synthesis of Biometallic Zinc Oxide Nanoparticles for Agricultural Application. *BioMetals* 2022, 35, 967–985. [CrossRef]