

Article

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

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Abstract: The development of new approaches for sustaining soil quality, leaf health, and maize productivity are imperative in light of water deficit and soil salinity. Plant growth-promoting rhizobacteria (PGPR) and silica nanoparticles (SiNP) are expected to improve soil chemistry leading to improved plant performance and productivity. In this field experiment, water deficit is imposed by three irrigation intervals—12 (I_1), 15 (I_2), and 18 (I_3) days. Plants are also treated with foliar and soil applications (control, PGPR, SiNP, and PGPR + SiNP) to assess soil enzymatic activity, soil physicochemical properties, plant physiological traits, biochemical analysis, nutrient uptake, and productivity of maize (*Zea mays* L.) plants grown under salt-affected soil during the 2019 and 2020 seasons. With longer irrigation intervals, soil application of PGPR relieves the deleterious impacts of water shortage and improves yield-related traits and maize productivity. This is attributed to the improvement in soil enzymatic activity (dehydrogenase and alkaline phosphatase) and soil physicochemical characteristics, which enhances the plants' health and growth under longer irrigation intervals (i.e., I_2 and I_3). Foliar spraying of SiNP shows an improvement in the physiological traits in maize plants grown under water shortage. This is mainly owing to the decline in oxidative stress by improving the enzymatic activity (CAT, SOD, and POD) and ion balance (K^+/Na^+), resulting in higher photosynthetic rate, relative water content, photosynthetic pigments, and stomatal conductance, alongside reduced proline content, electrolyte leakage, lipid peroxidase, and sodium content under salt-affected soil. The co-treatment of SiNP with PGPR confirms greater improvement in yield-related traits, maize productivity, as well as nutrient uptake (N, P, and K). Accordingly, their combination is a good strategy for relieving the detrimental impacts of water shortage and soil salinity on maize production.

Keywords: soil chemistry; chlorophyll pigments; electrolyte leakage; photosynthetic rate; nutrient uptake; enzymatic activity

1. Introduction

Global agricultural production is facing considerable obstacles not only from the increasing population, which is projected to rise more than 8 billion by 2030, but from climate change as well [1]. Soil salinity is one of the major limiting factors requiring special attention due to its deleterious impacts on germination, plant growth, and development. Per FAO appraisal, greater than 6% of the arable lands suffer from salinity [2]. Globally, more than 45 Mha of irrigated lands have been injured by salt, and 1.5 Mha are brought out of production every year due to soil salinity [3]. Therefore, there is a great need to improve plant performance and crop yield under salt stress to address the increment of global food needs [1,3,4]. The harmful impacts of soil salinity on plants are mostly manifested in some methods: Osmotic stress, ion imbalance, disruption of nutrient balances, oxidative damage by reactive oxygen species (ROS), metabolic disorders, and decrement of cell division [5]. Jointly, these impacts decrement plant growth, development, and ultimately crop productivity [6]. Osmotic stress induced by high soil salinity levels inhibited nutrient uptake and reduced the water uptake leading to physiological dehydration [7]. Plants exposed to soil salinity result in Na^+ competition with Ca^{2+} and K^+ in the cell membrane leading to osmotic imbalance and decreased photosynthesis. In recent years, several studies have been reported the pivotal role of some elements, especially in their nanoparticles (i.e., nano-silica) [8], to ameliorate the adverse effects of salinity stress in plants [9]. Furthermore, seed inoculation with plant growth-promoting rhizobacteria (PGPR) was proposed as an effective way to mitigate the toxic effects of soil salinity [10].

Concerning climate change, water deficit is the most imperative abiotic stress for declining the productivity of different crops in the arid and semiarid regions [11]. In the coming years, more severe bouts of inadequate moisture, low precipitation, and increment in mean and utmost temperatures are being predicted because of climate change which will adversely affect crop production [12]. Water deficit negatively affects the final yield and deteriorates metabolic activity, declines photosynthesis by decreasing chlorophyll content and reducing leaf area [13]. Water deficiency, especially during the critical growth stages, decreases leaf relative water content, transpiration rate, stomatal conductance, cell enlargement rate, and eventually impair plant growth [14]. Thus, a good understanding of the impact of deficit irrigation on maize growth and development is vital to crop management. As a result, unique techniques are required to alleviate the harmful outcomes of water stress to assure an incessant supply of food which reflects on increasing food security.

In recent years, plant growth-promoting rhizobacteria (PGPR) have obtained a lot of attention as they offer resistance to environmental stressors [15]. Several reports have stated that inoculation with PGPR is beneficial to plant growth and to reduce the abiotic stress of water deficit and soil salinity [16]. To tolerate the abiotic stress of water stress and soil salinity, PGPR assist plants by altering root morphology, resulting in better nutrient absorption, mineral solubilization, and improved soil moisture content [17]. The ACC deaminase enzyme produced by PGPR plays a vital role in decreasing ACC content through degrading ACC into α -ketobutyrate and ammonia [18], and then declines ethylene production in plants which constrains Na^+ and decline its absorption into plants.

Nanoparticles (NPs) as exogenous spraying and/or soil application have also received great interest recently owing to their ability to mitigate the deleterious effects of various soil stresses, such as salinity and drought, which positively influence the morpho-physiological growth traits in plants [19]. Silicon (Si) is the second most abundant element on the earth. It is not classified as a necessary element, but was newly implicated as a “quasi-essential” element by The International Plant Nutrition Institute [20]. Silica nanoparticles (nano- SiO_2) play a pivotal role in relieving the stressful features of abiotic (salinity and drought) stressors [21]. Exogenous application of nano- SiO_2 enhanced water status and carbon dioxide assimilation rate in plants by improving stomatal conductance and forming a double cuticle layer on the epidermis of leaves, resulting in reduced water loss through transpiration [22]. These nanoparticles are used to minimize the Na^+ content, increasing the activity of antioxidant enzymes, improve photosynthesis and increase nutrient uptake

under stressful conditions [23]. Therefore, spraying of nano-SiO₂ may improve plant tolerance to salt and water stressors [24]. Nevertheless, the information on the impacts of nano-SiO₂ on maize plants under environmental stressors is still insufficient; few reports have focused on the physiological role of nano-SiO₂ in plants.

Among cereal crops, maize (*Zea mays* L.) is considered the third most important cultivated grain worldwide owing to its improved adaptability to a wide spectrum of arid and semiarid conditions [25]. It is used as a staple food crop and has become the most efficient fodder raw material [26]. Globally, the cultivated area for maize was 201.8 Mha in 2020, with a total grain production of 1194.8 Mt, and in Egypt, the cultivated maize area was roughly 0.96 Mha, with a total grain production of 7.55 Mt [27]. As compared to other crops, Maize is a C₄ plant that is classified as moderately sensitive to water and salt stresses [28]. Therefore, a reduction in maize yield is expected in saline soils (electrical conductivity above 2 dS m⁻¹) due to osmotic stress and ion toxicity of higher accretion of Na⁺ in the leaves, which cause severe wilting. These saline conditions represent between 20 to 30% of the agricultural areas in the Middle East allocated for maize production.

To date, little research has described the impact of the combination of PGPR and SiNP on plant performance, and to the best of our knowledge, this investigation was never addressed before in maize plants grown under limited moisture availability in salt-affected soil. So, the novelty of this study was to determine the role of PGPR (inoculated to the seeds) and SiNP (exogenous spraying) as individual and combined treatments on saline soil physicochemical properties in addition to the effects on soil enzymes, osmoregulation, physiological and biochemical traits, yield, and related traits, as well as nutrient uptake in maize subjected to different irrigation intervals.

2. Materials and Methods

2.1. Experimental Layout and Treatments

Two field experiments were carried out at Sakha Agricultural Research Station, Agricultural Research Center (ARC), Egypt. The first experiment was conducted in the summer of 2019 and the other in the summer of 2020. The purpose of the experiments was to elucidate the influence of inoculation with plant growth-promoting rhizobacteria (*Azospirillum lipoferum* SP2 and *Bacillus circulans* NCAIM B.02324) and exogenous application of inorganic silica nanoparticles (500 mg SiNPs L⁻¹) as an individual application and/or combined application on soil properties and plant physiological, and biochemical characteristics along with nutrient uptake and productivity of maize plants (*Zea mays* L., cv. Hybrid single cross 10). Seeds were provided by the Maize Research Department, Sakha, Kafr El-Sheikh, Egypt, and characterized as a moderately salt-sensitive genotype. The characteristics of irrigation water used in this experiment are presented in Table 1. Plants were exposed to different irrigation intervals (12, 15, and 18 days) in salt-affected soil (EC, 7.3 dS m⁻¹). The investigation was performed as a split-plot based on a randomized complete block design (RCBD) with four replicates. The main plots were devoted to irrigation intervals, i.e., 12 (I₁), 15 (I₂), and 18 (I₃) days after sowing (DAS), while sub-plots were assigned to the soil and foliar applications (Control, PGPR, SiNP, coupled PGPR + SiNP). The sub-plot area was 42 m², including ten rows, 7 m long, and 70 cm apart. Plots were isolated by ditches of 1.5 m in width to avoid lateral movement of water. Planting was in hills 30 cm apart, and the seeding rate was 40 kg ha⁻¹. Maize seeds were planted on June 10th and 5th in the summer seasons of 2019 and 2020, respectively. Plants were thinned to one plant per hill before first irrigation. The preceding crop was wheat in both seasons. Nano-silica (NS) application rate was 500 mg L⁻¹ twice using hand atomizer and wetting agent at 20 and 30 days after sowing. The PGPR inoculation (provided from Bacteriology Lab., Sakha Agricultural Research Station, Kafr El-Sheikh, Egypt), were prepared as peat-based inoculums, 15 mL of 1 × 10⁸ CFU mL⁻¹ from each culture per 30 g of the sterilized carrier was mixed and carefully applied to maize grains using an adhesive. Then, it was spread away from the direct sun over a plastic sheet for a short time before sowing at a rate of 950 g ha⁻¹. Nitrogen fertilizer was applied in the form of urea (46.5% N) at the rate of 290 kg N ha⁻¹.

Phosphorus fertilizer was added in the form of calcium superphosphate (15.5% P_2O_5) at the rate of 75 kg P_2O_5 ha⁻¹ before sowing. All recommended agricultural practices were followed through the growing seasons according to the Ministry of Agriculture, Egypt. Weeds were hand-controlled continuously during maize vegetative growth.

Table 1. Irrigation water characteristics (IWC) were used in the experiment during the growing seasons 2019 and 2020.

Character	Season	pH	EC (dS m ⁻¹)	SAR	Na ⁺ (meq L ⁻¹)	Cl ⁻ (meq L ⁻¹)	SO ₄ ⁻ (meq L ⁻¹)	NH ₄ ⁺ (meq L ⁻¹)
IWC	2019	7.32 ± 0.21	0.53 ± 0.03	1.51 ± 0.12	1.92 ± 0.03	3.41 ± 0.04	0.13 ± 0.11	1.69 ± 0.12
	2020	7.21 ± 0.46	0.52 ± 0.04	1.48 ± 0.14	1.90 ± 0.02	3.32 ± 0.02	0.16 ± 0.14	1.79 ± 0.13

2.2. Meteorological Data

Sakha meteorological station data during the 2019 and 2020 summer seasons were recorded. Meteorological data were air temperature (°C), wind speed (km day⁻¹), relative humidity (%), and precipitation rate in Table 2.

Table 2. Meteorological data for the two summer growing seasons 2019 and 2020.

Year Month	2019				2020			
	Temperature (°C)		Wind Speed (km day ⁻¹)	RH (%)	Temperature (°C)		Wind Speed (km day ⁻¹)	RH (%)
	Max	Min			Max	Min		
June	35.6	18.0	119.1	67.5	36.5	16.4	111.0	66.4
July	36.9	22.9	95.1	65.5	35.0	22.0	121.1	65.1
Aug.	36.5	18.8	81.5	64.4	38.0	23.2	95.5	64.9
Sept.	32.5	18.5	82.3	69.5	37.4	24.8	86.2	68.4

max = maximum, min = minimum, RH = relative humidity, there was no precipitation during the growing period.

2.3. Soil Water Content Analysis Prior to Sowing

Soil water content was gravimetrically measured in soil samples taken from depths of 15 cm to 60 cm. Field capacity, permanent wilting point, bulk density, and available soil water were determined according to Arshad et al. [29], and presented in Table 3.

Table 3. Moisture content status of the experimental soil.

Soil Depth (cm)	Field Capacity (%)	Wilting Point (%)	Bulk Density (g/cm ³)	Available Soil Water	
				%	mm
0–15	47.75	26.94	1.18	20.81	34.34
15–30	41.36	25.13	1.23	16.23	28.24
30–45	38.43	23.55	1.28	14.88	27.01
45–60	35.39	21.82	1.36	13.57	26.87

2.4. Soil Chemical and Physical Characteristics Analysis Prior to Sowing

The soil of the experimental site was clayey in texture. Soil samples were collected by an auger from 0–30 cm depth and air-dried to determine the chemical and physical characteristics (Table 4).

2.5. PGPR Characteristics

In this investigation, two rhizobacterial strains, *Azospirillum lipoferum* SP2 and *B. circulance* NCAIM B.02324, were chosen based on their plant growth-promoting traits in a lab experiment to determine indole-3-acetic acid (IAA) and phosphate solubilizing activity under salinity and drought stresses [30]. These strains were obtained from the Department of Agricultural Microbiology, Soils, Water, and Environment Research Institute (SWERI), Agricultural Research Centre (ARC), Egypt. Jensen's Medium was used for growing

Azospirillum lipoferum SP2 [31], and King's B broth medium was used to grow *B. circulance* NCAIM B.02324 [32].

Table 4. Physicochemical characteristics of the experimental soil in the two growing seasons 2019 and 2020.

Character	2019	2020
pH (1:2.5 soil:water suspension)	8.25 ± 0.04 [†]	8.21 ± 0.01
Electrical conductivity (EC, dS m ^{−1}) [‡]	7.38 ± 0.02	7.33 ± 0.04
Soil organic matter (g kg ^{−1})	11.3 ± 0.04	11.8 ± 0.06
Exchangeable sodium percentage (%)	21.9 ± 0.54	21.2 ± 0.24
Particle size distribution (%)		
Sand	28.32 ± 1.74	28.17 ± 1.87
Silt	24.23 ± 2.07	24.55 ± 1.85
Clay	47.45 ± 2.45	47.28 ± 2.08
Texture grade	clayey	clayey
Soluble cations (meq L ^{−1}) [‡]		
Ca ²⁺	7.41 ± 0.74	9.31 ± 0.91
Mg ²⁺	5.56 ± 1.65	6.19 ± 1.33
Na ⁺	26.42 ± 2.12	22.59 ± 3.07
K ⁺	0.35 ± 0.06	0.41 ± 0.03
Soluble anions (meq L ^{−1}) [‡]		
CO ₃ ^{2−}	nd [‡]	nd
HCO ₃ [−]	4.59 ± 0.56	3.38 ± 0.75
Cl [−]	24.49 ± 1.11	18.19 ± 1.96
SO ₄ ^{2−}	15.15 ± 3.03	11.17 ± 3.12
Available macronutrients (mg kg ^{−1})		
N	9.65 ± 0.86	10.36 ± 1.69
P	8.31 ± 1.42	8.89 ± 1.49
K	351 ± 26.39	389 ± 24.29
Total counts of soil microbes		
Bacteria (CFU × 10 ⁷ g ^{−1} dry soil)	34 ± 1.06	41 ± 1.47
Fungi (CFU × 10 ⁴ g ^{−1} dry soil)	13 ± 0.07	19 ± 1.09
Actinomycetes (CFU × 10 ⁵ g ^{−1} dry soil)	24 ± 1.12	25 ± 1.39

[†] Standard deviation; [‡] not detected; [‡] measured in soil paste extract.

2.6. Nano Silica Characteristics

Silica (silicon dioxide) nanoparticles (SiNP) were provided by the Faculty of Agriculture, El-Sada Branch, AL-Azhar University, Egypt, and added to a nutrient solution. Silica nanoparticle properties were—99.5% purity and 10–20 nm particle size, specific surface area (270–330 m² g^{−1}), pH (4.0–4.5), and mean diameter (10 nm).

2.7. Determinations in the Soil after Sowing

2.7.1. Soil Enzymatic Activities

Soil dehydrogenase activity (DHA) was measured based on the technique of Dick et al. [33]. At 60 days after sowing, soil samples were collected at 0–20 cm depth to determine DHA. This approach included the soil incubation with a colorless, water-soluble substrate, TTC

(2, 3, 5-triphenyltetrazolium chloride), for 24 h at 25 °C. TTC is enzymatically declined to a colored, water-insoluble product, triphenyl formazan (TPF). By substituting oxygen and other naturally happening acceptors, TTC surpasses electrons, and protons detached by soil dehydrogenase activity from the oxidized organic compounds. After incubation, Triphenyl formazan is extracted from the soil with ethanol and spectrophotometrically measured at a wavelength of 485 nm. The results were expressed in mg TPF g⁻¹ soil d⁻¹.

Soil alkaline phosphatase activity (ALP) was measured based on the technique of Tabatabai and Bremner [34]. At 60 days after sowing, soil samples were collected at 0–20 cm depth to determine ALP. In this technique, a substrate (buffered disodium p-nitrophenyl phosphate hexahydrate solution) is applied to the collected samples, and the samples are incubated for 1 h at 37 °C. The p-nitrophenol (p-NP) compound, released by the activity of phosphatases is extracted, was colored with sodium hydroxide and measured spectrophotometrically at 400 nm. The activity of alkaline phosphatase was measured according to the calibration curve and was expressed in mg PNP g⁻¹ soil d⁻¹.

2.7.2. Soil Physicochemical Characteristics

Maize plants were harvested 120 days after sowing. At harvest, soil samples (0–30 cm depth) were collected with an auger and then homogenized to prepare a single representative sample for each replicate. The soil samples were dried in open air and ground. The soil was passed through a 2-mm sieve. The Ece (dS m⁻¹) was determined in soil paste extract using EC-meter (Genway, UK). However, pH was determined in 1:2.5 soil: distilled water suspension using pH-meter (Genway, UK). The exchangeable sodium percentage (ESP) and the sodium adsorption ratio (SAR) are measured subsequently calculating the concentration (meq L⁻¹) of Na⁺, K⁺, Ca²⁺, Mg²⁺ ions in soil paste extract using Atomic uptake Spectrophotometer (AAS, PERKIN ELMER 3300) with a detection limit of 100 ppb [29]. The SAR is a measurement of the ratio of sodium (Na⁺) ions to calcium (Ca²⁺) and magnesium (Mg²⁺). This is measured using the following formula, which described by Seilsepour and Rashidi [35]:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{([Ca^{2+}] + [Mg^{2+}])}{2}}}$$

Exchangeable sodium percentage (ESP) was measured based on the equation by Arshad et al. [29]:

$$ESP = 1.95 + 1.03 \times SAR \quad (R^2 = 0.92)$$

2.8. Determinations of Na⁺, K⁺ and K⁺/Na⁺ Concentrations in Maize Leaves

Na⁺, K⁺, and K⁺/Na⁺ concentrations were determined in the fourth topmost fully expanded leaves at 60 days after sowing. A 0.5 g oven-dry leaf sample was placed in a 50 mL conical flask and digested with 2.5 mL concentrated sulfuric acid on a hot plate at approximately 250 °C. Then repeatedly, small quantities of H₂O₂ were added until the digest remained clear. The samples were left to cool, and then transferred and diluted to 50 mL with ultra-pure water in a volumetric flask. Total sodium and potassium were determined according to Page et al. [36] using an atomic absorption spectrophotometer (AAS; Perkin Elmer 3300) with a detection limit of 100 ppb.

2.9. Determination of Physiological Characteristics in Maize Leaves

2.9.1. Photosynthetic Pigments Concentration

Chlorophyll and carotenoid concentration were determined in the fourth topmost fully expanded leaves at 60 days after sowing. Initially, 500 mg of leaf segments were cut into small pieces and extracted in 1 mL of 100% acetone for 48 h at 4 °C, these samples were homogenized, and then the extracted sap was centrifuged for 10 min at 3000× g and absorbance of the supernatant measured at 663 nm (for chlorophyll *a*), 645 nm (for

chlorophyll *b*), and 470 nm (for total carotenoids). Ultimately, the concentrations of the pigment were calculated based on the following equations [37]:

$$\text{Chl } a = 11.75 \times A_{662} - 2.35 \times A_{645}$$

$$\text{Chl } b = 18.61 \times A_{645} - 3.96 \times A_{662}$$

$$\text{Carotenoids} = 1.000 \times A_{470} - 2.27 \times \text{Chl } a - 81.4 \times \text{Chl } b / 227$$

2.9.2. Net Photosynthetic Rate (P_n)

The photosynthetic rate was measured in the topmost fully expanded leaf in the stem of the tagged plant at 60 days after sowing in all the treatments. The net photosynthetic rate was measured between 10.00 AM to 12.00 noon by an Infrared Gas Analyzer (TPS-2, PP systems), equipped with broadleaf cuvette (18 mm Ø chamber), under natural sunlight, carbon dioxide, and water vapor levels by the manufacturer's instructions.

2.9.3. Stomatal Conductance (g_s)

Stomatal conductance was measured with the AP4 porometer (Delta T Company, England) [38], in the ear leaf at 60 days after sowing. Each g_s measurement took around 1 h and started at 9:00, 12:00, or 15:00 h. Measurement in the front (r_a) and backside (r_b) of the center of the leaf. Total leaf conductance (g_s) is $1/r_l = 1/r_a + 1/r_b$.

2.9.4. Relative Water Content (RWC)

The measurement of RWC was performed based on the method of Turner and Kramer [39]. Harvested leaves were weighed directly to calculate the fresh weight (FW), followed by soaking in water in test tubes in the dark for 24 h. They were then blotted dry with filter paper, and weighed to calculate their turgid weight (TW). The dry weight (DW) was measured by drying the leaves in an oven at 70 °C for 48 h. The RWC (%) of each harvested leaf was measured with the following equation:

$$\text{RWC} = \frac{(FW - DW)}{(TW - DW)} \times 100$$

2.9.5. Free Proline Concentration (P_r)

Free proline content in the leaf tissue was determined using the method provided by Bates et al. [40]. An amount of 0.2 g of the fresh leaf was homogenized in 5 mL of 95% ethanol. The homogenate was centrifuged at $6000 \times g$. The supernatant was collected after two additional centrifugation cycles on the same homogenate residue using 5 mL of 70% ethanol. The collected supernatant was used for the estimation of proline content. The alcoholic extract was refrigerated at 4 °C. One mL of the alcoholic extract was diluted with 1 mL of distilled water and 2 mL of ninhydrin, and 2 mL of glacial acetic acid was applied; the mixture was then put in a boiling water bath for 1 h at 100 °C. The reaction was stopped by placing the test tubes in cold water. The samples were carefully mixed with 4 mL toluene. The light uptake of the toluene phase was determined at 520 nm using a UV Spectrophotometer. The proline concentration was estimated using a standard curve. Free proline concentration of leaves was expressed as $\mu\text{mol g}^{-1}$ FW of leaves.

2.9.6. Electrolyte Leakage (EL)

The topmost fully expanded leaves blade of 10 maize plants were collected, directly weighed, and cut into small pieces (ca. 1 cm). The small pieces originating from the same leaf were put into 20 mL of deionized water, and the rate of leakage was read at 1 min intervals for 60 min using a conductivity meter (CM 100 conductivity meter, John E. Reid and Associates, Chicago). The leakage rate was calculated as the slope of the line (generated from the time course of leakage) to the leaf dry weight. The method provided

by Sullivan [41] was used. The percentage of electrolyte leakage (EL%) was measured by the following formula:

$$EL = \frac{(\text{Initial conductivity})}{(\text{Final conductivity})} \times 100$$

2.10. Determination of Antioxidant Enzyme Activities and Lipid Peroxidation in Maize Leaves

Enzyme extracts were prepared by first freezing the weighed amount of leaves (1 g) in liquid nitrogen to prevent the proteolytic activity, followed by grinding with 5 mL of cold extraction buffer (0.1 M phosphate buffer, pH 7, containing 0.5 mM EDTA, and 2% (*w/v*) polyvinylpyrrolidone (PVP)), and centrifuged for 20 min at 10,000× *g* to use the supernatant as enzyme extract [42,43].

2.10.1. Catalase Activity (CAT)

CAT activity was estimated by measuring the initial rate of H₂O₂ disappearance by the method of Aebi [44]. The catalase estimation reaction mixture contained 50 mM Na⁺ phosphate buffer (pH 7.0), 20 µL/mL enzymatic extract and 1 mM H₂O₂. The disappearance of H₂O₂ was tracked by determining the decline of absorbance at 240 nm, and CAT activity [U (mg protein)^{−1}] was estimated by a molar uptake coefficient of 40 mM^{−1} cm^{−1} for H₂O₂.

2.10.2. Superoxide Dismutase Activity (SOD)

SOD activity was examined based on a method provided by Hammerschmidt et al. [45]. The reaction mixture comprised 50 mM Na⁺ phosphate buffer (pH 7.8), 100 µM EDTA, 20 µL/mL enzymatic extract and 10 mM pyrogallol. SOD activity [U (mg protein)^{−1}] was estimated by examining the reaction mixture for 120 s (at 60-s intervals) at 420 nm in a spectrophotometer.

2.10.3. Peroxidase Activity (POD)

Peroxidase (POD) activity was estimated by the technique of Kong et al. [46] in a 3.9 mL reaction mixture comprising 50 mM phosphate buffer (pH 7.0), 28 µL guaiacol, 100 µL enzymatic extract, and 19 µL H₂O₂. The absorbance was observed at 420 nm for a minimum 2 min at 30-s intervals; an absorbance change of 0.01 denoted one unit of POD activity.

2.10.4. Malondialdehyde Measurement (MDA)

Lipid peroxidation (MDA) was estimated by calculating the rate of malondialdehyde (MDA) by the method provided by Madhava and Sresty [47]. Roughly 1 g fresh weight was milled in 10 mL 10% trichloroacetic acid (TCA) by a mortar and pestle. The homogenate was centrifuged at 10,000 rpm for 20 min. The reaction mixture containing 2 mL extract and 2 mL thiobarbituric acid (TBA) was heated at 95 °C for 30 min, rapidly cooled on ice, and then centrifuged once more at 10,000 rpm for 20 min. The absorbance of the supernatant was estimated at 532 nm (A₅₃₂), 600 nm (A₆₀₀), and 450 nm (A₄₅₀), respectively, with a UV/VIS spectrophotometer. The malondialdehyde content was measured by the following formula:

$$\text{MDA content} = 6.45 (A_{532} - A_{600}) - 0.56 A_{450}$$

2.11. Maize Productivity

After 120 days from sowing, the harvest was done, ten plants were randomly collected from the fourth inner ridges to estimate yield traits. The number of grains per ear was measured by calculating the number of grains in five ears randomly selected in each subplot, and 100-grain weight was likewise estimated by the same five ears. Grain yield (kg ha^{−1}) was attained from the central area of each plot to prevent any border impact. Maize grain yield was adjusted to 15.5% moisture content. Biological air-dried yield (kg ha^{−1}) was

measured by harvesting the four central rows in each subplot. The harvest index was measured by the following formula:

$$\text{Harvest index (\%)} = \frac{(\text{Grain yield})}{(\text{Biological yield})} \times 100$$

where the biological yield = Grain yield + Straw yield

2.12. Nutrient Uptake

After 120 days from sowing, the harvest was done; grain samples were assembled, air-dried, crushed, and prepared for laboratory determination. Samples were wet-digested in concentrated sulfuric acid and hydrogen peroxide (H₂O₂). Macro-elements (nitrogen, phosphorus, and potassium) were estimated in grains according to the method provided by References [36,48,49], respectively. Along with nitrogen uptake (N_{uptake}), phosphorus uptake (P_{uptake}), and potassium uptake (K_{uptake}) in grains (kg ha⁻¹) were estimated by multiplying a percentage of the specified element (N, P, and K) by grain yield (kg ha⁻¹).

2.13. Statistical Analysis

Using split-plot analysis of variances (ANOVA), data were analyzed by software SPSS 20.0 for windows, and Duncan's multiple range test was used for comparison among the treatment means [50].

3. Results

3.1. Soil Enzymatic Activity

The impact of soil and foliar applications of either PGPR and/or SiNP on soil enzymatic activity are presented in Table 5. The statistical analysis of the data verified that significantly higher soil enzymatic activity (dehydrogenase and alkaline phosphatase) occurred when plants were treated with the sole or coupled treatment of PGPR and SiNP under water stress (I₂ and I₃) in salt-affected soil. DHA (mg TPF g⁻¹ soil d⁻¹) and ALP (mg PNP g⁻¹ soil d⁻¹) significantly declined in irrigation intervals I₂ and I₃ (15 and 18 days, respectively) compared to irrigation interval I₁ (12 days) during both the 2019 and 2020 seasons (Table 5). However, the synergistic treatment of PGPR and/or SiNP noticeably improved DHA and ALP under water stress (I₂ and I₃) in salt-affected soil. Remarkable improvement in soil enzymatic activity was found in maize plants in I₂ when treated with both SiNP and PGPR than untreated plants (control) in I₁ for both seasons. Likewise, soil enzymatic activity increased after exposing maize plants in I₃ with both SiNP and PGPR compared to control plants in I₂ for both seasons.

3.2. Soil Physicochemical Characteristics

The application of soil and foliar treatments altered soil physicochemical characteristics compared to the initial soil traits (Table 6). It was found that soil reaction (pH) decremented gradually with longer irrigation intervals (I₂ and I₃). However, exposure to a sole foliar application of SiNP resulted in a slight decline of the pH under all three irrigation intervals. The highest decline and improvement of soil reaction was observed with the combined application of PGPR+ SiNP in both the 2019 and 2020 seasons. The use of the individuals or combined application of SiNP and PGPR significantly influenced and improved the soil electric conductivity (EC) compared to untreated plants in both 2019 and 2020 seasons irrespective of irrigation interval (Table 6). Compared to the untreated plots post-harvest, sole application of PGPR exhibited a bigger improvement than the sole application of SiNP on EC irrespective of irrigation intervals for both seasons. The EC improved for plants in I₂ treated with both SiNP and PGPR compared to untreated plants in I₁, which had higher EC in both seasons. Likewise, the values of EC improved after exposing plants in I₃ to both SiNP and PGPR compared to untreated plants in I₂, which had higher EC in both seasons. The soil cations, i.e., Na⁺, K⁺, Ca²⁺, Mg²⁺, and ESP, were

measured and presented in Table 6. The combined SiNP and PGPR resulted in increased K^+ , Ca^{2+} , and Mg^{2+} ; whilst declining in the content of Na^+ and ESP irrespective of the irrigation interval during both 2019 and 2020. Applications of PGPR alone demonstrated greater improvements in soil chemistry than SiNP alone. Remarkable improvements of Na^+ , K^+ , Ca^{2+} , Mg^{2+} , and ESP were found for plants in I_2 treated with both SiNP and PGPR compared to untreated plants in I_1 in both seasons.

Table 5. The Soil enzymatic activities (0–20 cm profile) at harvest with irrigation intervals 12 (I_1), 15 (I_2), and 18 (I_3) days after sowing (DAS) in salt-affected soil treated with PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	DHA [®] (mg TPF g ⁻¹ soil d ⁻¹)		ALP [±] (mg PNP g ⁻¹ soil d ⁻¹)	
		2019	2020	2019	2020
I_1	Control	59 ± 2.2 cd	65 ± 2.1 cd	119 ± 1.3 e	131 ± 3.2 e
	PGPR [†]	63 ± 1.8 b	69 ± 2.2 b	139 ± 2.2 b	145 ± 2.4 b
	SiNP [‡]	60 ± 0.9 c	67 ± 2.1 c	127 ± 2.4 c	139 ± 2.5 c
	PGPR + SiNP	91 ± 3.2 a	97 ± 2.7 a	149 ± 3.1 a	161 ± 3.1 a
I_2	Control	47 ± 2.1 f	51 ± 2.4 f	95 ± 2.2 i	136 ± 2.2 i
	PGPR [†]	55 ± 3.1 d	65 ± 0.9 d	114 ± 1.3 f	148 ± 2.1 f
	SiNP [‡]	50 ± 2.5 e	61 ± 1.3 e	103 ± 1.7 g	140 ± 3.1 g
	PGPR + SiNP	62 ± 1.3 bc	70 ± 2.4 bc	122 ± 3.2 d	158 ± 3.5 d
I_3	Control	40 ± 3.1 i	43 ± 1.8 i	74 ± 2.2 l	140 ± 2.2 l
	PGPR [†]	45 ± 1.4 g	51 ± 2.4 g	91 ± 2.7 j	156 ± 2.4 j
	SiNP [‡]	41 ± 1.7 h	47 ± 1.4 h	80 ± 1.3 k	149 ± 3.3 k
	PGPR + SiNP	49 ± 2.4 ef	56 ± 2.4 ef	99 ± 3.5 h	169 ± 3.5 h
F-test					
Irrigation intervals (I)		***		***	
Soil and foliar treatments (SF)		**		**	
Interaction (I X SF)		ns		ns	

[®] dehydrogenase activity; [±] alkaline phosphatase activity; [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, and ns denote significance at $p < 0.001$, $p < 0.01$, and non-significant, respectively.

Table 6. Soil chemical parameters at the harvest of maize plants with irrigation intervals 12 (I_1), 15 (I_2), and 18 (I_3) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Year	(I)	(SF)	pH [‡]	EC [§] (dS m ⁻¹)	ESP [#] (%)	Na ⁺ [¶] (meq L ⁻¹)	K ⁺ (meq L ⁻¹)	Ca ²⁺ (meq L ⁻¹)	Mg ²⁺ (meq L ⁻¹)
2019	I_1	Control	8.02 ± 0.01 gh	4.46 ± 0.03 ef	12.13 ± 0.22 ef	15.66 ± 0.04 ef	0.53 ± 0.02 cd	15.99 ± 0.05 d	6.80 ± 0.03 d
		PGPR [†]	7.99 ± 0.02 i	4.10 ± 0.04 g	9.11 ± 0.33 g	11.73 ± 0.04 g	0.57 ± 0.04 b	18.57 ± 0.18 b	7.17 ± 0.01 b
		SiNP [‡]	8.01 ± 0.02 h	4.43 ± 0.06 fg	11.98 ± 0.12 fg	14.81 ± 1.02 fg	0.54 ± 0.05 c	16.22 ± 0.09 cd	7.18 ± 0.02 cd
		PGPR + SiNP	7.97 ± 0.02 j	3.98 ± 0.08 h	8.64 ± 0.11 h	9.13 ± 0.21 h	0.59 ± 0.03 a	20.43 ± 0.22 a	7.30 ± 0.01 a
	I_2	Control	8.09 ± 0.04 cd	4.84 ± 0.07 c	16.33 ± 0.36 c	19.44 ± 1.18 c	0.48 ± 0.00 ef	11.68 ± 0.15 fg	6.58 ± 0.08 fg
		PGPR [†]	8.04 ± 0.03 f	4.53 ± 0.05 e	13.89 ± 0.24 e	16.12 ± 0.95 e	0.52 ± 0.82 d	14.56 ± 0.08 de	6.85 ± 0.04 de
		SiNP [‡]	8.07 ± 0.04 e	4.77 ± 0.04 d	16.03 ± 0.35 d	18.67 ± 1.04 d	0.49 ± 0.01 e	11.98 ± 0.18 f	6.61 ± 0.05 f
		PGPR + SiNP	8.01 ± 0.02 g	4.41 ± 0.02 f	11.94 ± 0.15 f	15.06 ± 0.57 f	0.54 ± 0.03 c	16.96 ± 0.07 c	7.19 ± 0.07 c
	I_3	Control	8.16 ± 0.03 a	5.63 ± 0.06 a	23.95 ± 0.23 a	26.33 ± 0.78 a	0.44 ± 0.02 hi	7.92 ± 0.12 hi	6.17 ± 0.01 hi
		PGPR [†]	8.10 ± 0.02 c	5.04 ± 0.03 b	18.97 ± 0.24 b	20.73 ± 0.45 b	0.47 ± 0.03 g	10.29 ± 0.23 g	6.43 ± 0.07 g
		SiNP [‡]	8.15 ± 0.03 b	5.57 ± 0.05 ab	22.59 ± 0.35 ab	25.53 ± 0.38 ab	0.45 ± 0.01 h	8.19 ± 0.18 h	6.08 ± 0.02 h
		PGPR + SiNP	8.08 ± 0.03 d	4.78 ± 0.08 cd	16.39 ± 0.15 cd	18.82 ± 1.02 cd	0.49 ± 0.02 f	12.36 ± 0.25 e	6.61 ± 0.06 e

Table 6. Cont.

Year	(I)	(SF)	pH [‡]	EC [§] (dS m ^{−1})	ESP [#] (%)	Na ⁺ [°] (meq L ^{−1})	K ⁺ (meq L ^{−1})	Ca ²⁺ (meq L ^{−1})	Mg ²⁺ (meq L ^{−1})
2020	I ₁	Control	8.00± 0.01 gh	4.65 ± 0.03 ef	11.88 ± 0.22 ef	17.61 ± 0.75 ef	0.55 ± 0.02 cd	14.83 ± 0.15 d	6.85 ± 0.03 d
		PGPR [†]	7.97 ± 0.02 i	4.28 ± 0.04 g	8.87 ± 0.33 g	13.68 ± 0.08 g	0.59 ± 0.04 b	17.66 ± 0.07 b	7.23 ± 0.01 b
		SiNP [‡]	8.01 ± 0.02 h	4.63 ± 0.06 fg	11.86 ± 0.12 fg	16.76 ± 1.45 fg	0.56 ± 0.05 c	15.27 ± 0.05 cd	7.04 ± 0.02 cd
		PGPR + SiNP	7.86 ± 0.02 j	4.12 ± 0.08 h	8.48 ± 0.11 h	11.08 ± 0.01 h	0.61 ± 0.03 a	19.49 ± 0.02 a	7.35 ± 0.01 a
	I ₂	Control	8.07 ± 0.05 cd	4.94 ± 0.07 c	16.28 ± 0.36 c	21.41 ± 1.38 c	0.42 ± 0.00 ef	10.74 ± 0.05 fg	6.64 ± 0.08 fg
		PGPR [†]	8.02 ± 0.04 f	4.72 ± 0.05 e	13.94 ± 0.24 e	18.06 ± 0.49 e	0.54 ± 0.82 d	13.62 ± 0.18 de	7.18 ± 0.07 de
		SiNP [‡]	8.05 ± 0.02 e	4.96 ± 0.04 d	16.12 ± 0.35 d	20.62 ± 1.27 d	0.50 ± 0.01 e	11.12 ± 0.28 f	6.65 ± 0.04 f
		PGPR + SiNP	7.99 ± 0.05 g	4.59 ± 0.02 f	11.98 ± 0.15 f	17.11 ± 0.47 f	0.56 ± 0.03 c	15.87 ± 0.17 c	6.99 ± 0.06 c
	I ₃	Control	8.14 ± 0.03 a	5.81 ± 0.06 a	23.94 ± 0.23 a	28.28 ± 0.18 a	0.46 ± 0.02 hi	6.75 ± 0.22 hi	6.03 ± 0.01 hi
		PGPR [†]	8.08 ± 0.03 c	5.22 ± 0.03 b	18.45 ± 0.24 b	22.68 ± 0.25 b	0.49 ± 0.03 g	9.33 ± 0.33 g	6.50 ± 0.07 g
		SiNP [‡]	8.13 ± 0.03 b	5.76 ± 0.05 ab	22.36 ± 0.35 ab	27.47 ± 0.38 ab	0.47 ± 0.01 h	7.25 ± 0.28 h	6.14± 0.02 h
		PGPR + SiNP	8.06 ± 0.01 d	4.97 ± 0.08 cd	16.27 ± 0.15 cd	20.78 ± 1.25 cd	0.50 ± 0.02 f	11.41 ± 0.35 e	6.67 ± 0.06 e
F-test									
Irrigation intervals (I)			***	***	***	***	***	***	***
Soil and foliar treatment (SF)			***	***	***	***	***	***	***
Interaction (I X SF)			ns	ns	ns	ns	ns	ns	ns

[‡] pH is measured in soil:distilled water suspension at 1:2.5 ratio; [§] EC (electrical conductivity) is measured in soil:distilled water extract of 1:5; [#] ESP (exchangeable sodium percentage); [°] Ions (Na⁺, K⁺, Ca²⁺, and Mg²⁺) are measured in soil:distilled water extract of 1:5; [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha^{−1}; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L^{−1}. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). *** and ns denote significance at $p < 0.001$ and non-significant, respectively.

3.3. Na⁺, K⁺ and K⁺/Na⁺ Concentrations in Maize Leaves

Concerning irrigation treatments, increasing the irrigation intervals from I₁ to I₂, and I₃ caused increment of sodium content (Na⁺%), and decrement of potassium content (K⁺%) in maize leaves when plants grew in the absence of soil and foliar applications (Table 7). In contrast, Na⁺% declined, and K⁺% improved with soil application of PGPR and continued to decrease with the exogenous application of SiNP. However, the greatest reduction of Na⁺% and increase of K⁺% and K⁺/Na⁺ was in maize leaves grown with the combined application of PGPR and SiNP irrespective of irrigation interval. Exposing maize plants to combined SiNP and PGPR in I₂ reduced the sodium content, and increased potassium content compared to untreated plants in I₁ in both seasons, and similar results were found for the synergistic treatment in I₃ compared to the nontreated plant in I₂ (Table 7).

3.4. Chlorophylls and Carotenoids Concentration

In general, the pigment contents diminished when exposing plants to longer irrigation intervals. However, exogenous SiNP applications or PGPR soil applications and their combination improved plant growth and increments in chlorophyll *a*, *b*, and carotenoids irrespective of the irrigation intervals for both seasons. The values of pigment contents gradually increased with PGPR, while larger increases were observed with SiNP (Table 8). The greatest improvements in the concentrations of chlorophyll *a*, *b*, and carotenoids occurred with the combined treatment of both PGPR + SiNP compared to untreated plants. Integrated SiNP + PGPR treatments in the case in I₂ increased the pigment parameters compared to untreated plants (control) in I₁, and similar results occurred between the synergistic treatment in I₃ compared to untreated plants in I₂ (Table 8).

3.5. Physiological Characteristics of Maize Leaves

Longer irrigation intervals (I₂ and I₃) negatively affected physiological characteristics, such as photosynthetic rate (P_n), stomatal conductance (g_s), relative water content (RWC), proline content (P_r), and electrolyte leakage (EL) (Table 9). However, the physiological characteristics improved when plants were treated with sole or coupled applications

of PGPR and/or SiNP regardless of the irrigation interval. It was observed that the values of photosynthetic rate (P_n), stomatal conductance (g_s), and relative water content (RWC) slightly improved with soil application of PGPR. In contrast, greater improvements were observed when plants were sprayed with SiNP. Meanwhile, the greatest increase of photosynthetic rate (P_n), stomatal conductance (g_s), and relative water content (RWC) were seen with the synergistic application of PGPR + SiNP, which displayed more efficacy than individual applications relative to untreated plants for both seasons. Conversely, the values of proline content (P_r) and electrolyte leakage (EL) were decreased with soil application of PGPR and further declined when plants were sprayed with SiNP. Similarly, the maximum reduction of proline content (P_r) and electrolyte leakage (EL) were investigated with the coupled treatment of PGPR + SiNP that exhibited further efficacy than singular applications compared to untreated plants for both seasons. However, it was detected that integrated SiNP with PGPR in I_2 improved the physiological characteristics compared to untreated plants in I_1 and similar results occurred between the synergistic treatments in I_3 compared with the untreated plants in I_2 .

Table 7. The Na^+ , K^+ , and K^+/Na^+ concentrations in maize leaves of maize plants with irrigation intervals 12 (I_1), 15 (I_2), and 18 (I_3) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	Na^+ (%) [©]		K^+ (%) [±]		K^+/Na^+	
		2019	2020	2019	2020	2019	2020
I_1	Control	1.45 ± 0.07 h	1.15 ± 0.11 f	1.35 ± 0.08 e	1.42 ± 0.03 e	0.93 ± 0.04 e	1.23 ± 0.04 e
	PGPR [†]	1.22 ± 0.02 j	1.02 ± 0.05 h	1.57 ± 0.05 c	1.75 ± 0.02 c	1.28 ± 0.06 c	1.71 ± 0.06 c
	SiNP [‡]	1.06 ± 0.05 k	0.95 ± 0.05 i	1.85 ± 0.04 b	1.86 ± 0.04 b	1.74 ± 0.03 b	1.96 ± 0.03 b
	PGPR + SiNP	0.88 ± 0.04 l	0.83 ± 0.02 j	1.99 ± 0.06 a	1.98 ± 0.06 a	2.26 ± 0.02 a	2.38 ± 0.02 a
I_2	Control	1.71 ± 0.05 d	1.45 ± 0.05 d	1.24 ± 0.04 i	1.01 ± 0.03 i	0.73 ± 0.07 i	0.70 ± 0.07 i
	PGPR [†]	1.59 ± 0.08 f	1.23 ± 0.08 e	1.31 ± 0.07 g	1.22 ± 0.06 g	0.82 ± 0.03 g	0.99 ± 0.03 g
	SiNP [‡]	1.47 ± 0.02 g	1.15 ± 0.02 f	1.33 ± 0.08 f	1.34 ± 0.02 f	0.90 ± 0.05 f	1.17 ± 0.05 f
	PGPR + SiNP	1.36 ± 0.05 i	1.09 ± 0.05 g	1.42 ± 0.07 d	1.49 ± 0.07 d	1.04 ± 0.06 d	1.37 ± 0.06 d
I_3	Control	2.03 ± 0.11 a	1.79 ± 0.11 a	1.02 ± 0.04 k	0.73 ± 0.02 k	0.50 ± 0.01 k	0.41 ± 0.01 k
	PGPR [†]	1.85 ± 0.07 b	1.58 ± 0.07 b	1.15 ± 0.07 j	0.97 ± 0.04 j	0.62 ± 0.02 j	0.61 ± 0.02 j
	SiNP [‡]	1.74 ± 0.05 c	1.51 ± 0.05 c	1.19 ± 0.06 j	1.01 ± 0.04 i	0.68 ± 0.01 i	0.67 ± 0.01 i
	PGPR + SiNP	1.65 ± 0.05 e	1.39 ± 0.05 e	1.30 ± 0.06 h	1.09 ± 0.05 h	0.79 ± 0.01 h	0.78 ± 0.01 h
F-test							
Irrigation intervals (I)		***		***		***	
Soil and foliar treatments (SF)		**		**		***	
Interaction (I X SF)		ns		ns		ns	

[©] Sodium ion; [±] Potassium ion; [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, and ns denote significance at $p < 0.001$, $p < 0.01$, and non-significant, respectively.

Table 8. The photosynthetic pigments concentration (chlorophyll *a*, *b*, and carotenoids) at the leaves of maize plants with irrigation intervals 12 (I_1), 15 (I_2), and 18 (I_3) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	Chlorophyll <i>a</i> (mg g ⁻¹ FW)		Chlorophyll <i>b</i> (mg g ⁻¹ FW)		Carotenoids (mg g ⁻¹ FW)	
		2019	2020	2019	2020	2019	2020
I_1	Control	3.08 ± 0.02 d	3.35 ± 0.01 e	0.66 ± 0.01 e	0.80 ± 0.01 e	0.92 ± 0.06 e	0.96 ± 0.02 de
	PGPR [†]	3.65 ± 0.04 c	3.98 ± 0.02 c	0.75 ± 0.01 c	0.89 ± 0.02 c	1.25 ± 0.02 c	1.36 ± 0.06 b
	SiNP [‡]	3.97 ± 0.02 b	4.34 ± 0.03 b	0.78 ± 0.02 b	0.92 ± 0.03 b	1.43 ± 0.01 b	1.55 ± 0.01 b
	PGPR + SiNP	4.65 ± 0.01 a	4.88 ± 0.04 a	0.87 ± 0.02 a	0.98 ± 0.04 a	1.69 ± 0.03 a	1.75 ± 0.02 a
I_2	Control	2.09 ± 0.02 h	2.88 ± 0.03 i	0.48 ± 0.03 i	0.57 ± 0.02 i	0.54 ± 0.02 h	0.70 ± 0.02 gh
	PGPR [†]	2.88 ± 0.06 f	3.12 ± 0.06 g	0.59 ± 0.02 g	0.70 ± 0.01 g	0.71 ± 0.01 g	0.87 ± 0.02 f
	SiNP [‡]	3.09 ± 0.02 de	3.28 ± 0.04 f	0.62 ± 0.03 f	0.75 ± 0.01 f	0.80 ± 0.01 f	0.91 ± 0.02 e
	PGPR + SiNP	3.20 ± 0.05 cd	3.48 ± 0.03 d	0.69 ± 0.02 d	0.82 ± 0.02 d	0.95 ± 0.02 d	0.98 ± 0.03 d

Table 8. Cont.

Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	Chlorophyll <i>a</i> (mg g ⁻¹ FW)		Chlorophyll <i>b</i> (mg g ⁻¹ FW)		Carotenoids (mg g ⁻¹ FW)	
		2019	2020	2019	2020	2019	2020
I ₃	Control	1.29 ± 0.05 j	2.34 ± 0.06 l	0.35 ± 0.03 l	0.39 ± 0.04 l	0.39 ± 0.02 k	0.58 ± 0.01 k
	PGPR [†]	1.92 ± 0.02 i	2.66 ± 0.03 k	0.42 ± 0.03 k	0.48 ± 0.03 k	0.46 ± 0.02 j	0.64 ± 0.02 i
	SiNP [‡]	2.08 ± 0.02 h	2.85 ± 0.03 j	0.45 ± 0.04 j	0.52 ± 0.05 j	0.49 ± 0.04 i	0.66 ± 0.02 h
	PGPR + SiNP	2.22 ± 0.02 g	3.01 ± 0.04 h	0.50 ± 0.01 h	0.61 ± 0.03 h	0.56 ± 0.02 h	0.72 ± 0.01 g
F-test							
Irrigation intervals (I)		***		***		***	
Soil and foliar treatments (SF)		**		**		***	
Interaction (I X SF)		ns		ns		ns	

[†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, and ns denote significance at $p < 0.001$, $p < 0.01$, and non-significant, respectively.

Table 9. Physiological characteristics of maize leaves with irrigation intervals 12 (I₁), 15 (I₂), and 18 (I₃) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Year	Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	P _n ^Ω (μmol m ⁻² s ⁻¹)	g _s [¥] (μmol m ⁻² s ⁻¹)	RWC [#] (%)	P _r [€] (μmol g ⁻¹ FW)	EL ^π (%)
2019	I ₁	Control	15.36 ± 1.02 e	47.32 ± 1.60 e	85.2 ± 1.26 e	7.06 ± 0.04 h	18.32 ± 1.8 h
		PGPR [†]	17.65 ± 1.05 c	50.68 ± 2.37 c	91.3 ± 0.76 c	6.28 ± 0.03 j	15.32 ± 1.6 k
		SiNP [‡]	18.74 ± 1.08 b	51.74 ± 1.60 b	93.1 ± 1.80 b	6.06 ± 0.01 k	14.45 ± 1.4 j
		PGPR + SiNP	20.14 ± 1.12 a	53.12 ± 1.28 a	94.6 ± 1.22 a	4.12 ± 0.02 l	12.14 ± 1.2 l
	I ₂	Control	11.32 ± 1.14 i	43.51 ± 0.76 i	73.5 ± 1.60 i	7.83 ± 0.02 d	26.36 ± 1.3 d
		PGPR [†]	13.65 ± 1.15 g	45.96 ± 1.26 g	84.8 ± 1.37 g	7.24 ± 0.04 f	20.25 ± 1.7 g
		SiNP [‡]	14.25 ± 1.18 f	46.84 ± 0.02 f	85.3 ± 0.50 f	7.17 ± 0.03 g	19.14 ± 1.8 f
		PGPR + SiNP	16.36 ± 1.17 d	48.68 ± 2.04 d	86.5 ± 1.12 d	6.95 ± 0.03 i	16.65 ± 1.9 i
	I ₃	Control	7.54 ± 1.13 l	39.47 ± 2.14 l	51.8 ± 2.37 l	11.28 ± 0.05 a	44.47 ± 1.3 a
		PGPR [†]	10.85 ± 1.14 k	42.69 ± 2.19 k	59.8 ± 2.70 k	8.56 ± 0.03 b	35.65 ± 1.5 b
		SiNP [‡]	11.75 ± 1.15 j	43.65 ± 1.24 j	66.3 ± 1.46 j	8.14 ± 0.02 c	33.48 ± 1.7 c
		PGPR + SiNP	12.65 ± 1.11 h	44.75 ± 1.36 h	74.8 ± 1.60 h	7.65 ± 0.01 e	24.95 ± 1.1 e
2020	I ₁	Control	16.25 ± 1.08 e	48.32 ± 2.64 e	87.3 ± 1.28 e	5.98 ± 1.26 h	19.36 ± 1.8 h
		PGPR [†]	18.65 ± 1.07 c	52.32 ± 2.35 c	91.8 ± 1.61 c	5.12 ± 1.24 j	16.25 ± 1.6 k
		SiNP [‡]	20.65 ± 1.05 b	54.15 ± 2.25 b	93.7 ± 1.24 b	4.58 ± 1.66 k	15.24 ± 1.4 j
		PGPR + SiNP	22.14 ± 1.04 a	56.24 ± 1.15 a	95.6 ± 1.36 a	4.05 ± 0.76 l	13.14 ± 1.3 l
	I ₂	Control	10.65 ± 1.02 i	44.68 ± 1.45 i	73.0 ± 1.66 i	7.12 ± 0.03 d	27.65 ± 1.7 d
		PGPR [†]	12.74 ± 1.03 g	46.57 ± 3.75 g	87.5 ± 1.25 g	6.97 ± 0.03 f	21.45 ± 1.4 g
		SiNP [‡]	13.95 ± 1.12 f	47.87 ± 1.96 f	88.0 ± 0.35 f	6.74 ± 0.02 g	20.69 ± 1.9 f
		PGPR + SiNP	17.95 ± 1.15 d	50.22 ± 3.64 d	89.5 ± 0.70 d	5.76 ± 0.02 i	17.47 ± 1.8 i
	I ₃	Control	7.95 ± 1.14 l	40.14 ± 1.65 l	53.1 ± 2.04 l	9.04 ± 0.02 a	45.58 ± 1.6 a
		PGPR [†]	9.75 ± 1.18 k	42.65 ± 4.84 k	65.5 ± 1.26 k	7.75 ± 0.01 b	36.65 ± 1.5 b
		SiNP [‡]	10.55 ± 1.17 j	43.44 ± 2.75 j	69.8 ± 0.20 j	7.24 ± 0.02 c	34.45 ± 1.3 c
		PGPR + SiNP	12.07 ± 1.16 h	45.84 ± 1.36 h	78.6 ± 0.76 h	6.95 ± 0.04 e	25.33 ± 1.2 e
F-test							
Irrigation intervals (I)			***	***	***	***	**
Soil and foliar treatments (SF)			***	***	***	***	***
Interaction (I X SF)			***	***	***	***	ns

^Ω photosynthetic rate; [¥] Stomatal conductance; [#] Relative water content; [€] proline content; ^π electrolyte leakage. [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, and ns denote significance at $p < 0.001$, $p < 0.01$, and non-significant, respectively.

3.6. Antioxidant Enzyme Activities and Lipid Peroxidation in Maize Leaves

Longer irrigation intervals significantly increased the antioxidant enzymatic activity in maize leaves owing to limited moisture availability (Table 10). The lipid peroxidation significantly increased in the leaves of plants exposed to longer irrigation intervals. The largest increases by percentage in the activity of CAT, SOD, POD, and lipid peroxidation were found in the leaves of untreated plants in I₃. Nevertheless, the application of SiNP alone or in combination with PGPR resulted in clear reductions of CAT, SOD, POD, and MDA concentrations and alleviated the hazardous impact of oxidative stress regardless of the irrigation interval (Table 10). It was detected that leaves in the I₂ irrigation interval had reduced CAT, SOD, POD, and MDA activity when treated with PGPR + SiNP compared to the leaves of untreated plants in the I₁ interval for both seasons and similar results occurred between the synergistic treatment in I₃ compared with the untreated plants in I₂ (Table 10).

Table 10. The activity of antioxidant enzymes and lipid peroxidation in maize plants with irrigation intervals 12 (I₁), 15 (I₂), and 18 (I₃) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Year	Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	CAT [†] (Units mg ⁻¹ protein)	SOD [⊙] (Units mg ⁻¹ protein)	POD [♀] (Units mg ⁻¹ protein)	MDA ^Æ (nmol g ⁻¹ FW)
2019	I ₁	Control	0.05 ± 0.02 f	60.25 ± 1.25 h	0.08 ± 0.01 f	5.25 ± 0.01 f
		PGPR [†]	0.03 ± 0.004 h	55.24 ± 1.69 j	0.05 ± 0.02 g	4.36 ± 0.02 g
		SiNP [‡]	0.02 ± 0.007 hi	51.36 ± 1.36 k	0.03 ± 0.02 h	3.53 ± 0.05 gh
		PGPR + SiNP	0.01 ± 0.008 i	42.36 ± 1.114 l	0.02 ± 0.01 hi	2.56 ± 0.06 h
	I ₂	Control	0.09 ± 0.006 cd	92.36 ± 1.42 d	0.12 ± 0.02 d	7.54 ± 0.07 cd
		PGPR [†]	0.07 ± 0.007 e	76.54 ± 1.25 f	0.10 ± 0.03 e	6.35 ± 0.04 e
		SiNP [‡]	0.06 ± 0.009 ef	66.25 ± 1.01 g	0.09 ± 0.04 ef	5.67 ± 0.01 ef
		PGPR + SiNP	0.04 ± 0.002 fg	57.41 ± 1.05 i	0.07 ± 0.01 fg	4.78 ± 0.03 fg
	I ₃	Control	0.15 ± 0.001 a	110.36 ± 1.08 a	0.19 ± 0.04 a	12.65 ± 0.06 a
		PGPR [†]	0.12 ± 0.003 b	102.47 ± 1.18 b	0.16 ± 0.03 b	8.65 ± 0.07 b
		SiNP [‡]	0.10 ± 0.005 c	95.75 ± 1.25 c	0.14 ± 0.01 c	7.84 ± 0.04 c
		PGPR + SiNP	0.08 ± 0.004 d	86.89 ± 1.24 e	0.11 ± 0.02 de	7.28 ± 0.01 d
2020	I ₁	Control	0.07 ± 0.001 f	62.69 ± 1.11 h	0.11 ± 0.07 f	6.14 ± 0.01 f
		PGPR [†]	0.05 ± 0.005 h	57.58 ± 1.12 j	0.08 ± 0.04 g	5.47 ± 0.03 g
		SiNP [‡]	0.04 ± 0.007 hi	53.47 ± 1.09 k	0.06 ± 0.05 h	4.25 ± 0.06 gh
		PGPR + SiNP	0.03 ± 0.008 i	44.12 ± 1.18 l	0.05 ± 0.03 hi	3.58 ± 0.07 h
	I ₂	Control	0.12 ± 0.006 cd	94.45 ± 1.08 d	0.15 ± 0.02 d	8.36 ± 0.04 cd
		PGPR [†]	0.10 ± 0.008 e	78.78 ± 1.11 f	0.13 ± 0.01 e	7.69 ± 0.06 e
		SiNP [‡]	0.09 ± 0.009 ef	68.96 ± 1.12 g	0.12 ± 0.02 ef	6.78 ± 0.05 ef
		PGPR + SiNP	0.07 ± 0.002 fg	59.63 ± 1.13 i	0.10 ± 0.01 fg	5.45 ± 0.02 fg
	I ₃	Control	0.18 ± 0.003 a	112.52 ± 1.14 a	0.22 ± 0.03 a	13.12 ± 0.01 a
		PGPR [†]	0.15 ± 0.001 b	104.85 ± 1.15 b	0.19 ± 0.04 b	9.32 ± 0.07 b
		SiNP [‡]	0.14 ± 0.004 c	97.41 ± 1.19 c	0.17 ± 0.06 c	8.65 ± 0.03 c
		PGPR + SiNP	0.11 ± 0.005 d	88.74 ± 1.18 e	0.14 ± 0.05 de	8.08 ± 0.02 d
F-test						
Irrigation intervals (I)			***	***	***	***
Soil and foliar treatments (SF)			***	***	***	***
Interaction (I X SF)			ns	***	***	***

[†] Catalase; [®] Superoxide dismutase; [♀] Peroxidase; ^Æ Malondialdehyde; [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). *** and ns denote significance at $p < 0.001$ and non-significant, respectively.

3.7. Maize Productivity

The application of PGPR, SiNP, and their combination improved yield traits and productivity of maize grown under different irrigation intervals in salt-affected soil comparing with untreated plots (whereas neither PGPR nor SiNP was applied) (Table 11). Application of the combination (PGPR + SiNP) relieved the damaging impacts caused by water stress and soil salinity, as shown by the increased number of grains per ear, 100-grain weight,

grain yield, straw yield, and harvest index for both the 2019 and 2020 seasons. It was determined that synergistic applications of SiNP + PGPR in I₂ attained a similar number of grains per ear, 100-grain weight, grain yield, straw yield, and harvest index as control plants in I₁, and similar findings occurred between the synergistic treatment in I₃ and the control plants in I₂ (Table 11).

Table 11. Yield and yield components of maize plants with irrigation intervals 12 (I₁), 15 (I₂), and 18 (I₃) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Year	Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	Grains/Ear	100-Grain Weight (g)	Grain Yield (kg ha ⁻¹)	Straw Yield (kg ha ⁻¹)	HI [‡] (%)
2019	I ₁	Control	441.2 ± 4.23 cd	35.0 ± 0.3 de	5794.5 ± 30 d	9633.8 ± 63 cd	37.44 ± 0.2 c
		PGPR [†]	449.4 ± 2.36 bc	37.6 ± 0.2 c	6033.7 ± 40 b	9883.7 ± 55 b	37.91 ± 0.4 a
		SiNP [‡]	451.3 ± 3.65 b	37.9 ± 0.5 b	5905.3 ± 29 bc	9802.8 ± 68 bc	37.59 ± 0.1 ab
		PGPR + SiNP	456.1 ± 5.32 a	38.2 ± 0.2 a	6197.4 ± 35 a	10255.7 ± 72 a	37.67 ± 0.9 ab
	I ₂	Control	432.0 ± 3.25 ef	33.2 ± 0.3 fg	5484.5 ± 35 ef	9447.3 ± 59 ef	36.73 ± 0.3 e
		PGPR [†]	436.3 ± 3.65 de	33.9 ± 0.4 ef	5735.3 ± 40 d	9604.3 ± 57 d	37.39 ± 0.2 d
		SiNP [‡]	437.9 ± 3.98 d	34.0 ± 0.5 e	5684.3 ± 29 de	9504.6 ± 72 de	37.42 ± 0.4 cd
		PGPR + SiNP	443.4 ± 4.03 c	35.2 ± 0.6 d	5872.2 ± 36 c	9722.5 ± 65 c	37.66 ± 0.7 b
	I ₃	Control	421.4 ± 4.36 g	32.1 ± 0.6 j	5179.5 ± 44 h	9255.7 ± 55 g	35.88 ± 0.8 fg
		PGPR [†]	428.2 ± 4.65 fg	32.6 ± 0.5 i	5422.8 ± 51 fg	9408.3 ± 58 f	36.56 ± 0.9 ef
		SiNP [‡]	430.1 ± 4.98 f	32.9 ± 0.3 h	5305.2 ± 41 g	9365.4 ± 63 fg	36.16 ± 0.3 f
		PGPR + SiNP	434.7 ± 4.85 e	33.3 ± 0.2 g	5523.6 ± 29 e	9547.2 ± 66 e	36.65 ± 0.6 e
2020	I ₁	Control	445.1 ± 4.98 cd	36.5 ± 0.4 de	5865.4 ± 36 cd	9725.3 ± 66 d	37.62 ± 0.3 c
		PGPR [†]	449.4 ± 4.25 bc	38.6 ± 0.6 c	6245.6 ± 40 b	9933.4 ± 62 b	38.60 ± 0.1 a
		SiNP [‡]	450.6 ± 4.78 b	39.8 ± 0.3 b	6147.5 ± 34 bc	9894.3 ± 58 bc	38.32 ± 0.2 ab
		PGPR + SiNP	455.7 ± 4.58 a	42.3 ± 0.3 a	6325.4 ± 39 a	10344.2 ± 73 a	37.95 ± 0.4 b
	I ₂	Control	437.3 ± 4.25 ef	29.9 ± 0.4 gh	5584.6 ± 41 f	9573.8 ± 66 ef	36.84 ± 0.5 e
		PGPR [†]	442.8 ± 4.59 d	31.1 ± 0.2 fg	5874.3 ± 37 cd	9789.2 ± 72 cd	37.50 ± 0.6 c
		SiNP [‡]	441.0 ± 4.58 d	32.5 ± 0.4 f	5742.6 ± 33 de	9673.6 ± 69 de	37.25 ± 0.7 cd
		PGPR + SiNP	447.5 ± 4.69 c	36.8 ± 0.6 d	5905.8 ± 28 c	9868.6 ± 75 c	37.44 ± 0.8 c
	I ₃	Control	428.4 ± 4.26 g	23.5 ± 0.6 j	5299.3 ± 52 h	9373.2 ± 71 f	36.12 ± 0.9 fg
		PGPR [†]	433.2 ± 4.03 f	27.0 ± 0.7 ij	5567.4 ± 45 f	9513.2 ± 66 fg	36.92 ± 0.1 e
		SiNP [‡]	432.7 ± 4.08 f	27.8 ± 0.6 i	5475.9 ± 47 g	9489.3 ± 73 g	36.59 ± 0.2 ef
		PGPR + SiNP	438.3 ± 4.07 e	30.1 ± 0.3 g	5695.7 ± 35 e	9672.7 ± 77 de	37.06 ± 0.4 de
F-test							
Irrigation intervals (I)			***	***	***	***	***
Soil and foliar treatments (SF)			***	**	***	***	ns
Interaction (I X SF)			***	**	***	**	*

[‡] Harvest index; [†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, * and ns denote significance at $p < 0.001$, $p < 0.01$, $p < 0.05$ and non-significant, respectively.

3.8. Nutrient Uptake

The application of PGPR, SiNP, and their combination improved nutrient uptake (N, P, and K) of maize grown under different irrigation intervals in salt-affected soil compared with untreated plots (Table 12). Application of the combination (PGPR + SiNP) alleviated the harmful effects induced by low moisture availability and soil salinity by enhancing N uptake, P uptake, and K uptake in both the 2019 and 2020 seasons. This was followed by a sole application of PGPR and SiNP, respectively, when compared to the untreated plots (control) (Table 12). Though, it was noticed that coupled SiNP + PGPR in I₂ increased N_{uptake}, P_{uptake}, and K_{uptake} to greater amounts than in untreated plants in I₁. Similar findings coupled SiNP + PGPR with irrigation interval I₃ likewise augmented N_{uptake},

P_{uptake} and K_{uptake} in comparison with untreated plants (control) with irrigation interval I_2 in 2019 and 2020 seasons (Table 12).

Table 12. Grains NPK uptake at the harvest of maize plants with irrigation intervals 12 (I_1), 15 (I_2), and 18 (I_3) days in salt-affected soil treated by PGPR and Si nanoparticles during the 2019 and 2020 seasons.

Irrigation Intervals (I)	Soil and Foliar Treatments (SF)	N_{uptake} (kg ha ⁻¹)		P_{uptake} (kg ha ⁻¹)		K_{uptake} (kg ha ⁻¹)	
		2019	2020	2019	2020	2019	2020
I_1	Control	95.69 ± 1.2 d	97.95 ± 2.1 d	54.76 ± 1.4 d	57.48 ± 1.4 d	95.69 ± 2.1 d	99.71 ± 2.3 d
	PGPR [†]	100.76 ± 2.3 b	104.93 ± 2.2 b	58.53 ± 1.8 b	63.08 ± 1.2 b	103.18 ± 2.34 b	107.42 ± 2.5 b
	SiNP [‡]	99.21 ± 2.4 bc	103.89 ± 2.3 bc	57.87 ± 1.1 bc	62.70 ± 2.2 bc	101.57 ± 2.5 bc	106.35 ± 2.4 bc
	PGPR + SiNP	104.74 ± 1.8 a	107.53 ± 2.8 a	61.35 ± 0.9 a	65.15 ± 2.3 a	107.22 ± 2.6 a	110.06 ± 2.5 a
I_2	Control	84.46 ± 2.7 g	86.56 ± 1.4 g	44.42 ± 1.3 g	46.35 ± 1.5 g	83.36 ± 2.7 g	85.44 ± 2.7 g
	PGPR [†]	95.21 ± 1.4 de	98.10 ± 1.5 de	48.18 ± 1.5 de	51.11 ± 1.1 de	92.91 ± 2.4 de	95.75 ± 2.4 de
	SiNP [‡]	94.93 ± 1.5 e	96.48 ± 1.2 e	50.59 ± 1.8 e	52.83 ± 1.2 e	95.50 ± 2.5 e	97.05 ± 2.5 e
	PGPR + SiNP	99.24 ± 1.7 c	100.99 ± 1.7 c	56.96 ± 1.7 c	59.06 ± 1.1 c	99.83 ± 2.8 c	102.17 ± 2.3 c
I_3	Control	73.55 ± 1.9 i	75.78 ± 2.5 i	31.59 ± 1.6 i	34.45 ± 1.2 i	75.10 ± 2.6 i	78.43 ± 2.8 i
	PGPR [†]	79.72 ± 2.1 hi	82.40 ± 2.4 hi	36.33 ± 1.3 hi	39.53 ± 1.3 hi	83.51 ± 2.3 hi	86.85 ± 2.7 hi
	SiNP [‡]	80.64 ± 2.2 h	83.78 ± 2.3 h	38.73 ± 1.1 h	41.62 ± 1.4 h	82.76 ± 2.2 h	85.97 ± 2.6 h
	PGPR + SiNP	86.17 ± 2.8 f	89.42 ± 1.9 f	44.74 ± 2.1 f	48.41 ± 1.6 f	87.83 ± 2.8 f	91.13 ± 2.7 f
F-test							
Irrigation intervals (I)		***		**		***	
Soil and foliar treatment (SF)		**		***		***	
Interaction (I X SF)		***		ns		**	

[†] Plant growth-promoting rhizobacteria (PGPR) is applied at the rate of 950 g ha⁻¹; [‡] Silica nanoparticles (SiNP) are applied at the rate of 500 mg L⁻¹. Means of the same growing season designated with different letters indicate significant differences among treatments according to the Duncan's test ($p < 0.05$). Values are means ± standard deviation (SD) from four replicates (Means ± SD). ***, **, and ns denote significance at $p < 0.001$, $p < 0.01$, and non-significant, respectively.

4. Discussion

In the future, a great reduction in the yield of field crops (especially in arid and semiarid zones) is anticipated owing to limited soil moisture availability and increased soil salinity (Table 11). As a result, there is an imperative to alleviate the harmful impact of water stress and soil salinity, while also optimizing the physiochemical soil characteristics (Table 6) and plant physio-biochemical characteristics (Table 9) to mitigate the effects of climate change effects, such as diminished water supplies especially in the Mediterranean basin [51]. Maize plants are classified as a medium sensitive to salt, and therefore, adequate irrigation water is pivotal during water shortage which otherwise resulted in reduced yield traits [52], such as lowered grain yield [53]. Numerous techniques, which are cost-effective, such as foliar application in the form of engineered silica nanoparticle (SiNP) and soil applications with plant growth-promoting rhizobacteria (PGPR), to mitigate water stress and saline soil. In the present study, their combined effect on water shortage and salt-affected soil was investigated. Silica nanoparticles obviously enhanced the growth of maize plants under different irrigation intervals (i.e., I_1 , I_2 , and I_3). Furthermore, the combined application of PGPR and SiNP clearly encouraged the development of maize plants under limited moisture availability, caused by longer irrigation intervals, when compared with a recommended irrigation interval (I_1). Treated plants with the coupled PGPR and SiNP possessed the highest soil physicochemical characteristics, plant physio-biochemical characteristics, and nutrient uptake compared to untreated plots (control). Our results exhibited that coupled SiNP and PGPR are more effective in augmenting productivity under low soil moisture in salt-affected soil.

4.1. Effect of PGPR and SiNP on Soil Enzymatic Activities and Physicochemical Properties

The water shortage and soil salinity are characterized primarily by poor soil structure, aeration, surface crusting, high pH, and low filtration rate. Therefore, plants, particularly their roots, cannot develop in such circumstances; furthermore, osmotic pressure constrains

water and nutrient absorption resulting in declined soil enzymes activity (Table 5) and soil physicochemical properties [54]. PGPR plays an important role in increasing soil water content because of its properties to improve soil hydrological parameters [54], which cause increases in soil enzyme activity and improved soil health. The increased activity of soil enzymes in response to the addition of PGPR due to the improvement of soil structure, soil particulates, and polysaccharides from microbial cells [55]. As a result, improved water holding capacity, porosity, aeration, and infiltration, which aid roots in penetrating the soil and help escape from salinity to access more water. Foliar application of SiNP decreased the harmful impacts of water deficit on plant growth and maize productivity. In this respect, foliar application of SiNPs may modify the uptake and acquisition of nutrients in various plant species by stimulating the binding of nutrients in plant tissues, and by affecting their translocation into shoots [56]. SiNP addition retained the plant's photosynthetic capacity through improved leaf health and avoidance of leaf abscission resulting in improvement of plant performance (Table 9). Moreover, SiNP application increased cell membrane stability and integrity, which caused an increase in soil enzyme activity (Table 5). Further increases of dehydrogenase and alkaline phosphatase activities in response to the combination of PGPR and SiNP, might be attributed to increased soil water holding capacity, improved soil chemistry and osmoregulation, as well as root exudates, which improve the microbial respiration rate and natural microbial flora [57]. These results are consistent with Alsaedi et al. [58], who stated that there was a positive correlation between phosphate solubilizing bacteria and phosphatase activity. Soluble salts weaken the soil quality resulting in harmful impacts on crop growth and development [59]. PGPR could enhance nutrients in soil solution by increasing K^+ , Ca^{2+} , and Mg^{2+} , leading to reduced Na^+ content in the rhizosphere, which causes osmotic stress (Table 6). Application of PGPR improved soil chemical properties due to its porous structure, large surface area, negative surface charge, high water holding capacity, and improved cation exchange capacity (CEC) that possesses the essential elements, resulting in improved plant development for maize plants with increasing irrigation interval under salt-affected soil [60]. Application of PGPR solely or integrated with SiNP declined soil pH, EC, Na^+ , and ESP, which ultimately augmented Ca^{2+} , Mg^{2+} , and K^+ under water stress in salt-affected soil (Table 6). PGPR application caused metabolic balance where Na^+ (low) and K^+ or Ca^{+2} (high) are required for optimal physiological processes and water uptake alongside nutrient uptake. These results were in accordance with Mahmood et al. [61], which indicated the strong relationship between the application of PGPR and soil aggregates on the excreted polysaccharides in the soil.

4.2. Effect of PGPR and SiNP on Ions Equilibrium in Maize Leaves

Application of PGPR modulated ion balance and boosted K^+ in leaves by lessening Na^+ in leaves (Table 7). Inoculation of *Azospirillum lipoferum* strains SP2 (auxin producing), and *Bacillus circulance* in maize plants under water and salt stress increased K^+ absorption and Na^+ elimination [62]. Nano-silica treated plants could maintain normal cell metabolism under osmotic stress despite the declined leaf water potential in the 18-day irrigation interval (I_3) due to improved ion balance (increased K^+ to high levels and decreased Na^+ to low levels in the maize leaves). PGPR improved plant-water relations as demonstrated by the higher leaf RWC, which can be explained by improvements in the root hydraulic conductivity and osmoregulation in the leaves [63]. Similarly, decreasing the content of Na^+ ions in leaves under the coupled application of PGPR + SiNP might be referred to as the exopolysaccharide activity of PGPR that binds the Na^+ ions leading to a decline in its uptake by plant root. While silicon could mediate the imbalance induced by Na^+ ions by regulating the uptake, transport, and distribution of Na^+ ions [64].

4.3. Effect of PGPR and SiNP on Photosynthetic Pigments and Physiological Characteristics

Photosynthetic pigments and physiological characteristics play a crucial role in improving leaf health and crop performance [65]. It is proven that maize plants are sensitive to the harmful impact of water shortage and salt-affected soil, which results in a decline in

photosynthetic pigments and physiological characteristics due to deficient biosynthesis. Nevertheless, foliar application of silica nanoparticles displayed a substantial capability to boost the biosynthesis of photosynthetic pigments, like chlorophyll *a*, chlorophyll *b*, and carotenoids under drought and salinity stress (Table 8) [66–68]. Likewise, beneficial impacts of exogenous application of silicon on chlorophyll content, photosynthetic rate, stomatal aperture, osmolytes content, and the activity of antioxidants have been previously stated in maize plants [69]. Foliar application of silica nanoparticles stimulated water uptake and stomatal conductance by influencing hydraulic conductivity and transpiration rate [70]. Furthermore, nano-silica addition retained the plant's photosynthetic capacity through improved leaf health and reduced leaf abscission resulting in improved plant performance [71]. Maize plants inoculated with *Bacillus circulance* amplified root hydraulic conductivity in comparison with untreated plants when subjected to drought and salinity. The application of PGPR promoted carbohydrate metabolism and transport, which is positively reflected in chlorophyll pigments and antioxidant enzymatic activities, causing increased productivity [72]. Combination of PGPR and SiNP induced mineralization, organic acids, and augmented plant nutrient availability. Chlorophyll, carotenoids, photosynthetic rate, relative water content, and stomatal conductance in leaves augmented, while proline content and electrolyte leakage declined by increasing the irrigation interval to 18 days (I_3) under salt-affected soil (Table 9). Electrolyte leakage (EL%) and proline content significantly augmented with the increase of irrigation interval to I_2 and I_3 compared to I_1 in 2019 and 2020 (Table 9). This increment is linked to exposure of plants to water shortage in salt-affected soil; these findings are in accordance with [73]. These findings could be owing to the injurious impact of water shortage on plasma membrane function and dehydration of cytoplasm, causing increments in EL and P_r content in maize plants under water stress. Application of coupled PGPR and SiNP resulted in improved leaf health linked with declined electrolyte leakage and proline content. The beneficial impact of PGPR and SiNP in lessening EL and P_r content due to their function in maintain plasma membrane stability and enhancing RWC along with declined oxidative stress led to diminished lipid peroxidation. These findings are in accordance with [57]. It was found that the coupled application of PGPR and SiNP increased chlorophyll pigments and physiological attributes due to improvements in soil physicochemical properties and osmoregulation in water and salt stress conditions. These results are in harmony with those recorded by Reference [60].

4.4. Effect of PGPR and SiNP on Antioxidant Enzymatic Activities and Lipid Peroxidation

According to our results, antioxidant enzymatic activities like CAT, POD, and SOD were significantly amplified with longer irrigation intervals (Table 10). The highest CAT, POD, and SOD activity were detected in the maize plants exposed to I_3 , followed by the plants that were exposed to irrigation interval I_2 in comparison with the recommended irrigation interval of I_1 (Table 10). Under environmental stresses, such as water stress and soil salinity stress, the high antioxidants enzymatic and non-enzymatic activities in plants consider crucial to deal with the damaging impacts of ROS by scavenging excess ROS to prevent oxidative damage [43,65,73]. Consequently, the maize plants treated with coupled PGPR and SiNP under irrigation water shortage and salt-affected soil improve antioxidant enzymatic activity in comparison with stressed untreated plants and control plants and have been noted by Moussa [70]. Moreover, nano-silica foliar application increased cell membrane stability and integrity, and decreased oxidative damage by improving antioxidant enzymatic activity, such as CAT, POD, and SOD. So, in accordance with [70], it appears that nano-silica enhances osmotic regulation and leaf water content under water shortage. This proved that the application of nano-silica not only maintained leaf water content, but also protects the plant by preserving the structure and activity of macromolecules [26]. Malondialdehyde (MDA) is a cytotoxic product and designates the degree of lipid peroxidation. The application of *Azospirillum lipoferum* SP2 and *Bacillus circulance* in combination with SiNP were stimulatory to lipid peroxidase (Table 10). PGPR and SiNP application has been noticed to diminish the MDA content under salinity and water stressors [22,74]. This is an

important benefit of PGPR and SiNP in to be capable of relieving the oxidative damage and other harmful impacts caused by ROS. Also, the synergistic application of PGPR and SiNP reduced the electrolyte leakage, which may have further resulted in a decline in MDA content, as well as the combination treatment stimulated, improved antioxidant enzymatic activity [75], and decreased the MDA contents.

4.5. Effect of PGPR and SiNP on Yield Traits and Productivity

Concerning yield-related traits and productivity, environmental stressors, such as water shortage and soil salinity, hinder water and nutrient uptake, decrease physiological characteristics, and increase oxidative stress. As aforementioned in (Tables 7–10), minimized yield-related traits occurred mainly in the number of grain per ear and 100-grain weight (Table 11). The lessening in yield-related traits was significant with the longer durations in irrigation intervals (I_2 and I_3) in comparison with the recommended irrigation interval (I_1) in salt-affected soil. This injurious effect of water shortage may be attributable to the damaging influences on cell division and elongation, delayed cellular growth, declined photosynthetic rate, and eventually minimized yield-related traits, as well as productivity (i.e., grain yield, straw yield, and harvest index). In salt-affected soil, the resulting water shortage had a harmful impact on crop productivity [73]. Conversely, the yield-related traits of maize plants considerably improved with coupled applications of PGPR and SiNP; the increment was significant in the stressed treated plants in comparison with stressed untreated plants. These findings exhibited that, PGPR and SiNP have the capacity to increase plant development, water and nutrients absorption, and subsequently maximize yield-related traits and productivity [51].

4.6. Effect of PGPR and SiNP on Nutrient Uptake

In the current study, the increase of irrigation interval to 15 and 18 days (I_2 and I_3) significantly decreased the absorption of N, P, and K in maize grains in comparison with the recommended irrigation interval of 12 days (I_1) (Table 12). This resulted in limited nutrient uptake owing to lowered transpiration, immobility and availability of ions in the soil, reduced membrane permeability, and poor absorption of plant root [76]. Abou El Hassan et al. Stated a significant decline in N, P, and K uptake with increasing duration of water deficit [77]. Decreasing nutrient uptake could be attributed to limited soil moisture availability and osmotic stress, which lessens the solubility of nutrients resulting in a decline of ions around root hairs [73]. The inoculation of PGPR with foliar spraying of nano-silica to maize plants maximized the essential macroelements in the soil, which augmented nitrification and holding water and nitrogenous nutrients in the rhizosphere compared to control plots. The results detected that the exogenous spraying with SiNP and inoculation with PGPR alone or coupled significantly maximized N, P, and K absorption under water shortage in salt-affected soil (Table 12). P activity and fixation in alkaline soils are decreased by water deficit. Nevertheless, foliar application of nano-silica augmented P and K uptake, owing to the alleviation of osmotic pressure, increased water holding capacity, and improved root function under water stress. In addition, nano-silica could maintain higher amounts of K in the leaves and prevent leaf water depletion and increase K uptake. These findings are in accordance with the research on rice and barley, where nano-silica had a positive impact on ameliorating phosphorus deficiency have been described [28,78,79]. Singular application of PGPR could mitigate the detrimental effect of water shortage on maize yield by maintaining water holding and osmoregulation, resulting in improved soil enzymatic activity and soil physicochemical properties. Nevertheless, it was noticed that the co-application with nano-silica further improved ion balance, plant physiological and biochemical attributes under limited moisture availability in salt-affected soil, resulting in increased yield productivity and nutrient uptake.

5. Conclusions

Our results demonstrated that limited soil moisture availability and osmotic stress reduce plant growth, yield-related traits, and productivity in maize plants. However, inoculation of PGPR recovered soil health due to improved soil enzymatic activity and soil physicochemical properties, as well as improved the plant's water and nutrient status through improved water holding capacity and osmoregulation, which positively reflected on plant performance. Additionally, exogenous spraying of nano-silica (SiNP) stimulated vegetative growth and improved leaf health due to increased chlorophyll content, pigments, improved physiological traits, potassium transport, antioxidant enzymatic activity, and decreased oxidative stress, proline content, electrolyte leakage, lipid peroxidase, and sodium content which eventually positively reflected on yield-related traits. In conclusion application of PGPR in combination with SiNP could mitigate the harmful impact of longer irrigation intervals for maize plants are grown in salt-affected soil. Moreover, further improvement was detected in soil health, growth, leaf health, and plant development, reflecting on maximizing nutrient uptake, yield-related traits, and productivity of maize plants treated with the coupled PGPR + SiNP under water shortage and soil salinity. This approach could be a distinctive technique for sustainable agricultural development.

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