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Rhizobium Enhanced Drought Stress Tolerance in Green Bean Plants Through Improving Physiological and Biochemical Biomarkers

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DUE to global warming and climate change, drought is considered one of the major abiotic stressful conditions that causes numerous morphological, physiological, and biochemical changes that limit the plant growth and productivity. The enhancement of drought tolerance by the application of plant growth-promoting rhizobacteria has been progressively documented. Therefore, the present study was carried out to examine the potential role of *Rhizobium leguminosarum* biovar. *Phaseoli* in attenuating the adverse effects of water deficiency (80, and 60% of the estimated crop evapotranspiration) on growth, yield and quality and some biochemical and physiological parameters of green bean plants cv. Valentino. The experimental design was a randomized complete block design with three replications. The obtained results revealed that increasing water deficit severity resulted in decreases in plant growth characteristics, leaf nutrient content, SPAD readings, leaf relative water content (LRWC), leaf membrane stability index (LMSI) and yield components, as well as induced increments in proline content, catalase, peroxidase, and superoxide dismutase activities. However, application of *Rhizobium leguminosarum* considerably improved all growth and yield parameters and enhanced SPAD readings, RWC, MSI, proline content, and antioxidant enzyme activities. It could be concluded that *Rhizobium leguminosarum* inoculation could be used as a promising and sustainable strategy to cope with the adverse impacts of drought stress on green bean productivity in the forthcoming era of climate change.

Keywords: *Phaseolus vulgaris*, Water stress, PGPR, Proline, Antioxidant, Water use efficiency (WUE).

Introduction

Drought is the most destructive abiotic stress that limits the growth and productivity of plants (Del-Canto et al., 2023), and due to global climate change, which is expected to increase in the forthcoming years, mainly in arid and semi-arid areas. The World Resources Institute (WRI, 2019) ranks Egypt as the 43rd most water-stressed country out of 164 countries. Green bean (*Phaseolus vulgaris* L.) belongs to the Fabaceae family and is cultivated worldwide due to its high nutritional value (Mehrasa et al., 2022). Egypt is ranked 7th among the largest producers of green beans. The cultivated area was 26028 ha, with

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a total production of about 265 thousand tonnes and an average yield of 10.18 tonnes ha^{-1} in 2020 (FAOSTAT, 2022). It is well known that green beans are a drought-sensitive crop (Rai et al., 2020). Drought stress obstructs growth, water and nutrient uptake, and photosynthesis and ultimately triggers a substantial reduction in plant yield (Teferi et al., 2022 and Rizzo et al., 2023).

Drought stress dramatically affected the whole plant metabolism through the overproduction of reactive oxygen species (ROS) that resulted in the oxidation of biomolecules such as proteins, lipids, DNA and RNA, causing cell death under severe water scarcity (Raja et al., 2020). To counter the harmful and lethal effects of ROS, plants accumulate some osmoprotectants like proline to maintain cell turgidity and induce various enzymatic and non-enzymatic antioxidants to scavenge the ROS (Foyer and Noctor, 2016). These mechanisms may be improved by the application of some plant growth-promoting rhizobacteria, which hold the potential to attenuate these damaging impacts in a sustainable way (Gupta et al., 2022 and Iqbal et al., 2023) *via* the modification of phytohormone activities, antioxidant activities, the production of microbial volatile organic compounds, 1-aminocyclopropane-1-carboxylate (ACC) deaminase, osmolytes, and/or exopolysaccharides (Ahmad et al., 2022).

Among these exploited rhizobacteria, *Rhizobium leguminosarum* bv. *Phaseoli* which belongs to the Rhizobiaceae, is known for its symbiotic relationship with leguminous plants. It was found that *Rhizobium leguminosarum* significantly increased the root length and yield of *Brassica napus* (Noel et al., 1996 and Taye et al., 2022). Several studies demonstrated that the application of *Rhizobium leguminosarum* promoted and improved drought stressed plants of *Vicia faba* (Mansour et al., 2021; Amine-Khodja et al., 2022 and Álvarez-Aragón et al., 2023) and *Pisum sativum* (Álvarez-Aragón et al., 2023) through physiological and biochemical changes.

Thus, the current study was based on the hypothesis that application of *Rhizobium leguminosarum* bv. *phaseoli* to green bean plants exposed to water deficiency conditions would improve green bean tolerance to drought stress. With this aim, this work was conducted to assess the role of *Rhizobium leguminosarum* bv. *phaseoli* in ameliorating the detrimental effects of drought stress on the growth, yield, and quality and some physio-chemical parameters of green bean plants.

Materials and Methods

Experimental site and plant material

The experiment was carried out in lysimeters of 2 m^2 filled with washed sand soil during the 2020 and 2021 seasons at the Experimental Farm of the Horticulture Department, Agriculture Faculty, Ain Shams University, Shoubra El Kheima, Qalyubiyah Governorate, Egypt. Seeds of green bean cv. Valentino were sown in rows with a space of 60 cm between rows and 10 cm along the row on the 1st of September in both seasons. For each plot, the plant density was 15 plants m^{-2}. All agricultural management practices for green bean production, fertilization, diseases, and pest control were followed according to the recommendations of the Egyptian Ministry of Agriculture.

Experimental layout

The experimental design was a randomized complete block design with three replicates. Three irrigation water levels (100, 80, and 60% of the estimated crop evapotranspiration, ET_c) were used. The irrigation water quantities were carried out with a specific amount irrigation water during plant life. The amounts of irrigation water were calculated using the following formula:

$$\mathbf{ET_c = ET_o \times KC}$$

Where, $\mathbf{ET_c}$ = crop evapotranspiration, $\mathbf{ET_o}$ = reference evapotranspiration (mm/day), and **KC** = crop coefficient.

The $\mathbf{ET_o}$ values were calculated by a class evaporation pan obtained from the nearest metrological station in Bahtim, Shoubra El Kheima, Qalyubiyah Governorate, Egypt.

The active bacterium of *Rhizobium leguminosarum* bv. *phaseoli* was obtained from the Bio-fertilizers Unit, Agriculture Faculty, Ain Shams University. Non-inoculation (control) and *Rhizobium leguminosarum* treatments were used. A volume of 5 ml of the microbium (108 CFU/ml) was dranched around each seedling that were 7 days old and repeated three times at 15-day intervals (7, 22 and 37 days after sowing).

Data Recorded

Vegetative Growth Parameters

Three plants/replicate were randomly collected 52 days after sowing to record vegetative growth parameters, i.e., plant length, number of leaves per plant, and fresh and dry weights of shoot and root systems. The fourth fully expanded mature leaf from the top of five plants was used to calculate the average leaf area as a relation between area unit and dry weight of leaves using the following equation (Koller, 1972):

$$\text{Leaf area (cm}^2) = \frac{\text{Disk area} \times \text{No.Disk Leaf DW}}{\text{Disk DW}}$$

Determination of Leaf Mineral Contents

In an acid-digested solution of dried leaf samples, total nitrogen, potassium, and calcium, and magnesium were measured using a Kjeldahl method (UDK 149 automatic Kjeldahl analyzer, VELP Scientific, Inc., Bohemia, NY, USA), a flame emission photometer method (JENWAY, PFP-7, ELE Instrument Co. Ltd., Essex, UK), and an atomic absorption spectroscopy method (Analyst 200, Perkin Elmer, Inc., Massachusetts, USA), respectively, according to the procedures of Chapman and Pratt (1982). Furthermore, phosphorus was determined using a spectrophotometer method (SPECTRONIC 20D, Milton Roy Co. Ltd., Houston, USA). according to Watanabe and Olsen (1965).

Physiological Parameters

Samples of fresh fully expanded mature leaves were taken from the fourth leaf from the plant apex of five plants per each replicate to measure the physiological parameters. Leaf chlorophyll content as SPAD readings were measured using a portable chlorophyll meter (SPAD-502; Konica Minolta Sensing, Inc., Japan). Leaf relative water content (LRWC) was determined according to the method of Kaya et al. (2003). The leaf membrane stability index (LMSI) was appraised following the methodology of Shi et al. (2006).

Biochemical Parameters

The fourth fresh fully expanded mature leaf from the plant apex was used for determining the biochemical parameters. Total leaf free proline content was estimated as described by Khare et al. (2012). Catalase (EC 1.11.1.6) activity was measured following the method of Montavon et al. (2007). The activity of peroxidase (EC 1.11.1.7) was assayed by the method of Hammerschmidt et al. (1982). The activity of superoxide dismutase (EC 1.15.1.1) was assayed using the method of Beauchamp and Fridovich (1971).

Yield Parameter Measurements and Water Use Efficiency (WUE)

Green pods were harvested at commercial maturity after 60 days from sowing, and the total number of pods per plant, pod length, pod diameter, and pod yield were recorded. Furthermore, water use efficiency was calculated as pod yield per quantity of irrigation water applied according to Hoffman et al. (2007) as follows:

$$\text{WUE} = \frac{\text{Pod yield (g)}}{\text{Applied irrigation wate}(l)} \left(\frac{g}{l}\right)$$

Principal Component Analysis (PCA)

A principal component analysis was performed using the XLSTAT software to determine the relationship between the studied and evaluated parameters and the experimental factors (*Rhizobium* treatment (with and without) under different irrigation levels (100, 80 and 60% ET_c).

Statistical Analysis

Data obtained were subjected to a statistical analysis using the CoStat package program for Windows (version 6.303; CoHort Software, USA), a combined ANOVA analysis was performed to estimate the differences among the treatments across the two growing seasons using Bartlett's test for homogeneity of variances. The means were separated using Duncan's multiple range test at $P \leq 5\%$ level of significance according to Gomez and Gomez (1984).

Results and Discussion

The current experiment was carried out to evaluate the favorable effects of *Rhizobium leguminosarum* bv. *Phaseoli* on the morphological, and physiobiochemical parameters of green bean plants grown under different irrigation levels (100, 80 and 60% ET_c). The experiment revealed the following results:

Vegetative Growth Parameters

Increasing water deficiency levels significantly decreased all vegetative growth parameters. The combined analysis indicated that the increases were found to be 10.51 and 30.14% for plant length, 18.48 and 49.68% for number of leaves per plant, 23.16 and 76.72% for leaf area, 19.06 and 50.78% for shoot fresh weight, 32.26 and 73.16% for root fresh weight, 15.97 and 34.02% for shoot dry weight, and 32.76 and 71.80% for root dry weight at 80 and 60% ET_c, respectively, compared with the check plants (100% ET_c), as shown in Figs. 1 and 2. Several studies revealed that drought stress significantly decreased vegetative growth traits in faba bean (Ouzounidou et al., 2014, Ammar et al., 2015, Amine-Khodja et al., 2022 and Essa et al., 2023), snap bean

(Ibrahim et al., 2021), and groundnut (Sabra et al., 2023). These reductions may be attributed to decrease the photosynthesis capacity, and the expansion, and division of plant cells (Sundaravalli et al., 2005 and Rodriguez et al., 2008), as well as to the decrease the levels of auxins, cytokinins, and gibberellins, which have several adverse impacts on plant growth (Farooq et al., 2012). Application of *Rhizobium leguminosarum* significantly enhanced all these parameters under well-watered and water-limited conditions compared with the respective controls. Similar results were obtained by Amine-Khodja et al. (2022) who found that the growth parameters of faba bean were significantly affected by *Rhizobium* inoculation under water deficit conditions. In addition, Sabra et al. (2023) reported that the *Rhizobium*-groundnut symbiosis exhibited a remarkable improvement in plant growth parameters under water stress. The stimulatory effect of *Rhizobium* application on green bean plant growth may be attributed to the production of auxins, biological nitrogen fixation produced by the bacterium (Anjum et al., 2011), and/or enhanced water and mineral nutrient uptake (Etesami and Maheshwari, 2018) through enhancing root system proliferation by the production of IAA and ACC deaminase (Diby et al., 2005).

Leaf Mineral Content

Data in Fig. 3 obviously reveal that decreasing water irrigation level from 100 to 60% ET_c caused significant decreases in leaf macronutrient contents, i.e., N, P, K, Ca, and Mg. Several works have depicted that water deficit reduced nutrient availability and nutrient contents in plant leaves (Cetinkaya et al., 2016 and Abdelaal et al., 2021). However, *Rhizobium leguminosarum* application considerably improved N, P, K, Ca, and Mg contents compared with the respective check plants under all water regimes. These increments in nutrient content may be due to the fact that PGPR increased root growth with

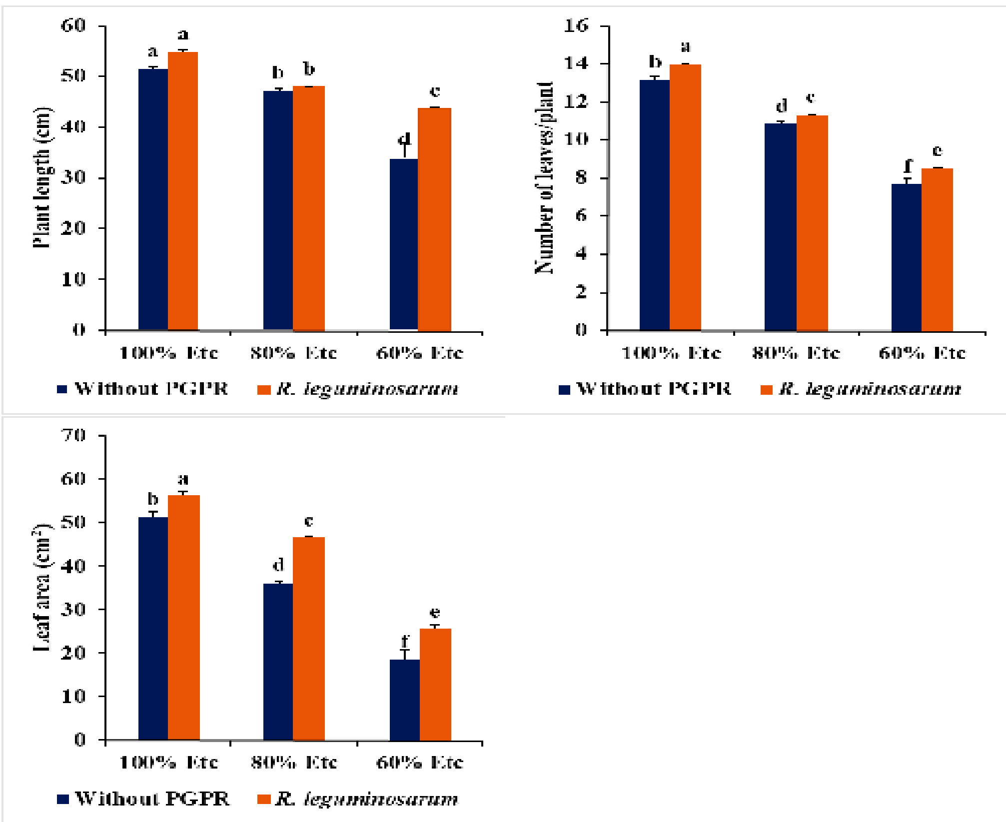

Fig. 1. Effect of Rhizobium leguminosarum bv. Phaseoli application on plant length, number of leaves/plant and leaf area of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

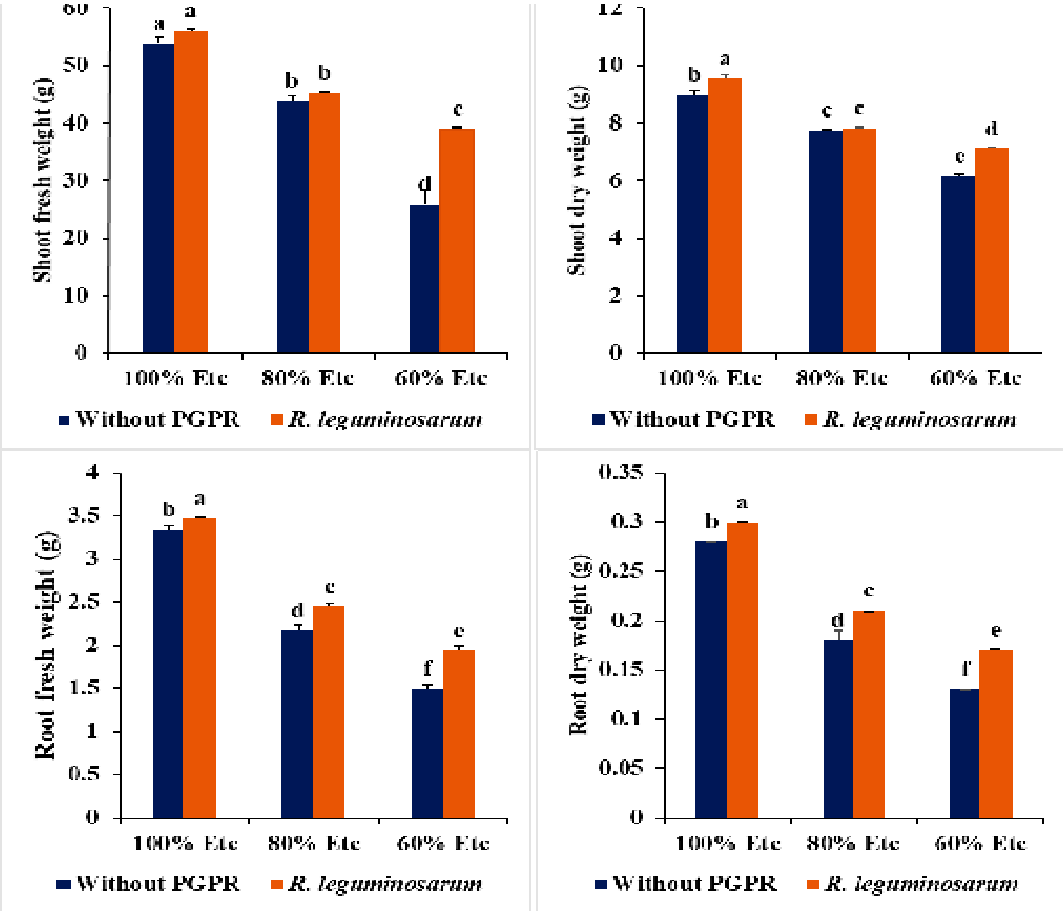

Fig. 2. Effect of Rhizobium leguminosarum bv. Phaseoli application on fresh and dry weights of shoot and root systems of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

a subsequent increase in water acquisition and nutrient uptake (Paul and Sarma, 2006) which is expected to enhance the movement of nutrients from soil to root. In addition, the enhancement of nitrogen content in the leaves is due to the ability of *Rhizobium* to the biological nitrogen fixation in the soil and makes it available for root uptake (Etesami and Maheshwari, 2018). Moreover, it was found that PGPR enhanced the availability and uptake of these nutrients *via* enhancing the solubility of phosphorus and iron (Etesami and Maheshwari, 2018).

SPAD Readings, Leaf Relative Water Content (LRWC) and Leaf Membrane Stability Index (LMSI)

From Fig. 4, it is noted that water scarcity had significant negative impacts on leaf chlorophyll content as SPAD readings, LRWC and LMSI. Decreasing irrigation level from 100 to 60% ETc led significantly to decrease SPAD readings, LRWC and LMSI by about 20.90, 30.48, and 34.47%, respectively. In this regard, these decreases in leaf greenness, LRWC and LMSI under drought stress are in line with the decreases in plant growth parameters (Figs. 1 and 2). Previous studies reported similar results for other crops (Ors et al., 2016, Igiehon and Babalola, 2021, Amine-Khodja et al., 2022, Alghamdi et al., 2023 and Ferioun et al., 2023). It is well known that drought stress causes a decline in relative water content, followed by a decline in transpiration rate (Farooq et al., 2012). The turgor pressure also declined when water levels decreased, which subsequently caused cell damage, and a reduction in plant growth and development (Castillo et al., 2013). However, inoculation

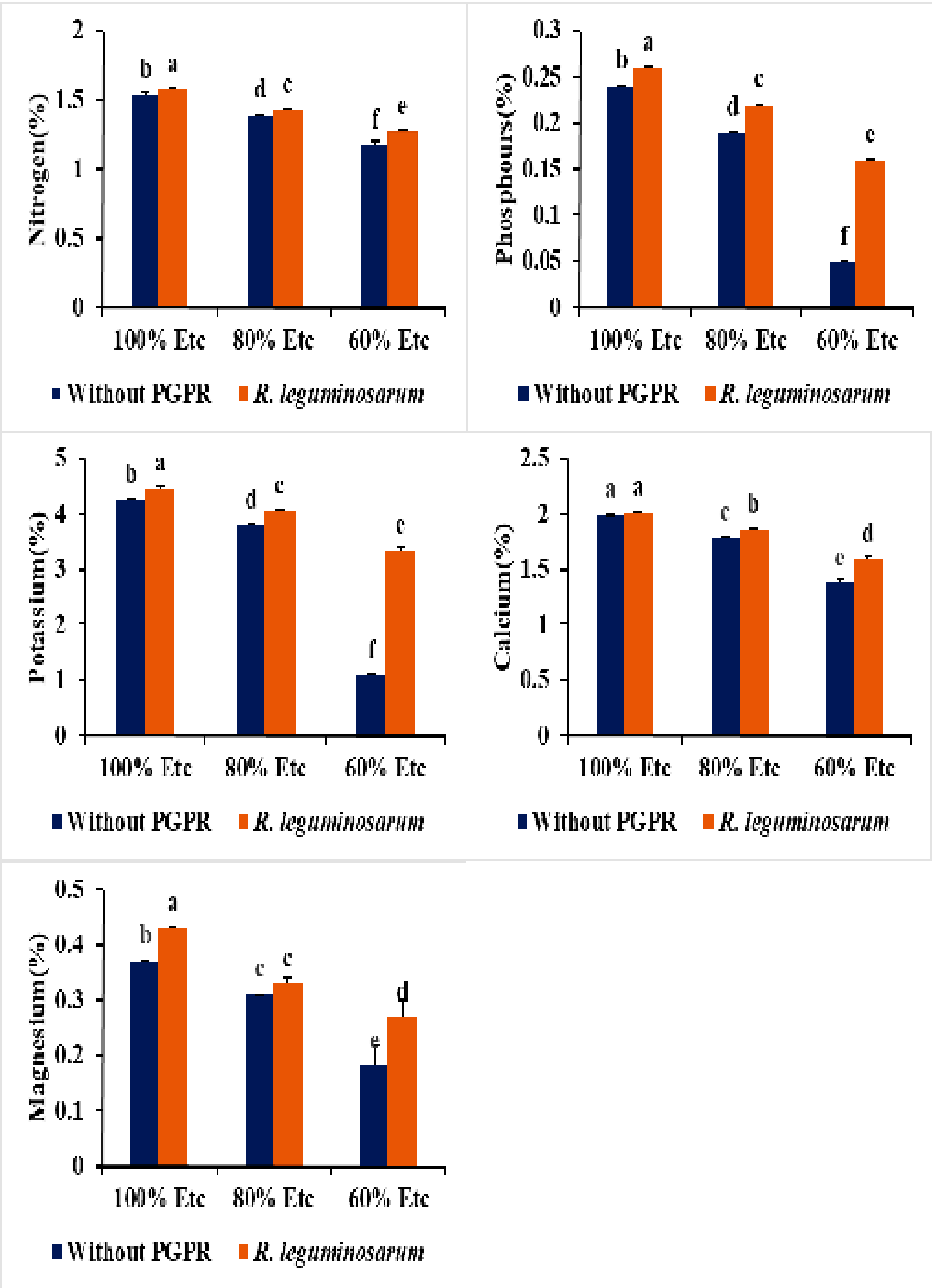

Fig. 3. Effect of Rhizobium leguminosarum bv. Phaseoli application on leaf macronutrient contents of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

with *Rhizobium leguminosarum* attenuated the detrimental impacts of water deficiency on these parameters. Similarly, *Rhizobium leguminosarum* significantly increased leaf chlorophyll content in faba bean (Amine-Khodja et al., 2022), and in groundnut (Sabra et al., 2023), and improved LRWC in soybean (Igiehon and Babalola, 2021) under drought stress. It is well documented that PGPR adjusts water potential by adjusting the hydraulic conductivity, opening of stomata, and transpiration rate (Basu et al., 2021). In addition, previous studies demonstrated that PGPR treatment efficiently improved growth of lateral roots, and fibrous rootlets that are responsible for water and nutrient absorption, and subsequently enhanced the relative water content (Khan and Bano, 2019). Also, it is believed that increasing relative water content *via* PGPR treatment may be ascribed to bacterial IAA production of phytohormones and osmoprotectants substances (Kudoyarova et al., 2019). Enhancing leaf relative water content resulted in a reduction of damage to

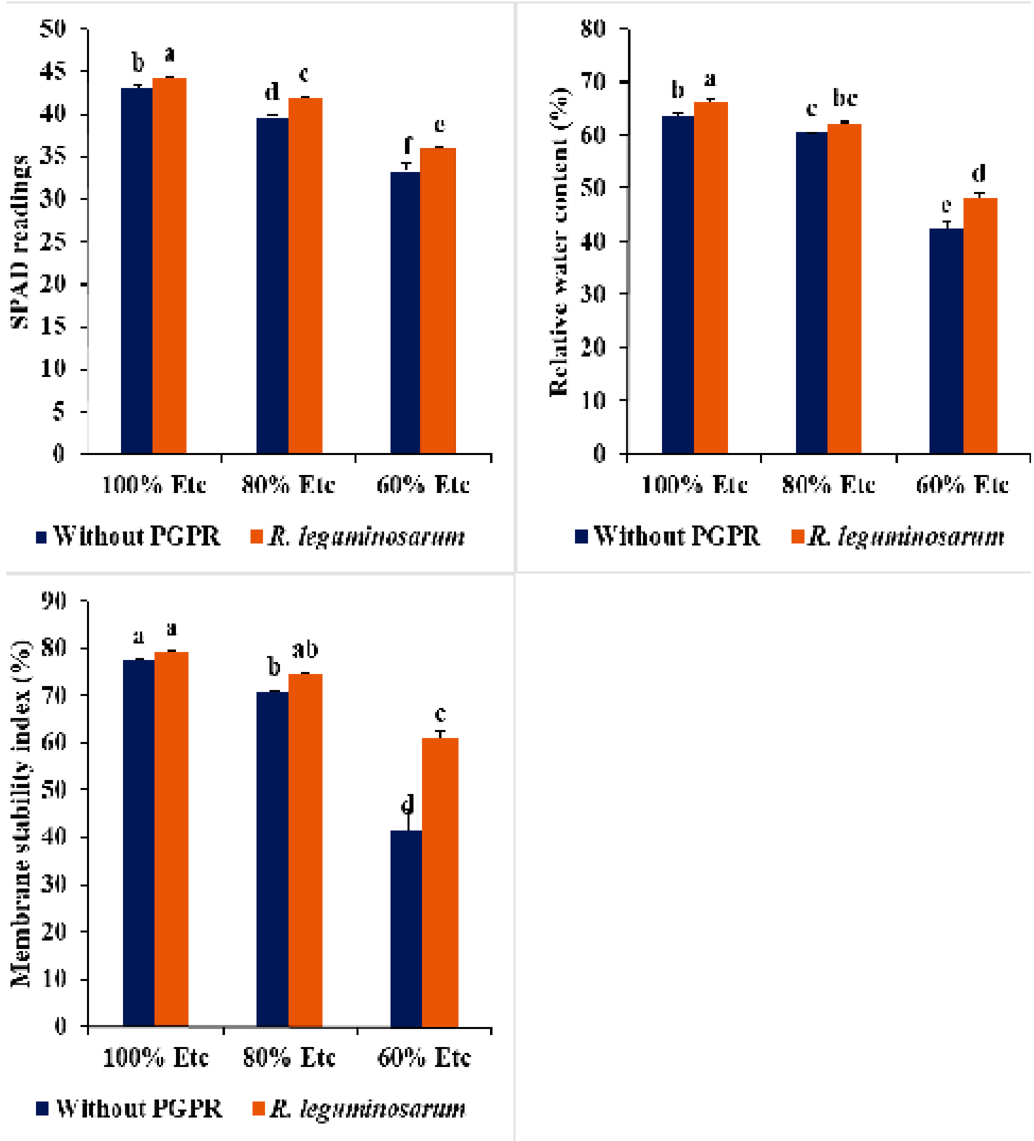

Fig. 4. Effect of Rhizobium leguminosarum bv. Phaseoli application on SPAD readings, leaf relative water content and leaf membrane stability index of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

cell membranes and as a consequence, improved the membrane stability index.

Proline Content

Proline is an important biochemical indicator for drought stress tolerance in a variety of plants since its accumulation by plant tissues is an adaptive response. In this study, drought stress treatments resulted in significant accumulations of proline by 38.49 and 63.60% at 80 and 60% ET_c, respectively, compared with the well-watered plants (Fig. 5). These findings confirmed that proline content strongly increased with exposure plants to drought stress conditions. Similar results were obtained in pea (Alexieva et al., 2001), chickpea (Mafakheri et al., 2010), and faba bean (Amine-Khodja et al., 2022 and Essa et al., 2023). Moreover, proline content had a strong positive correlation with drought tolerance (Ghiabi et al., 2013). *Rhizobium leguminosarum* application markedly increased proline accumulation in comparison with the non-treated plants under all water deficit levels. Amine-Khodja et al. (2022) reported similar results in faba beans. Proline accumulation in plants exposed to drought stress plays an important role in maintaining turgor

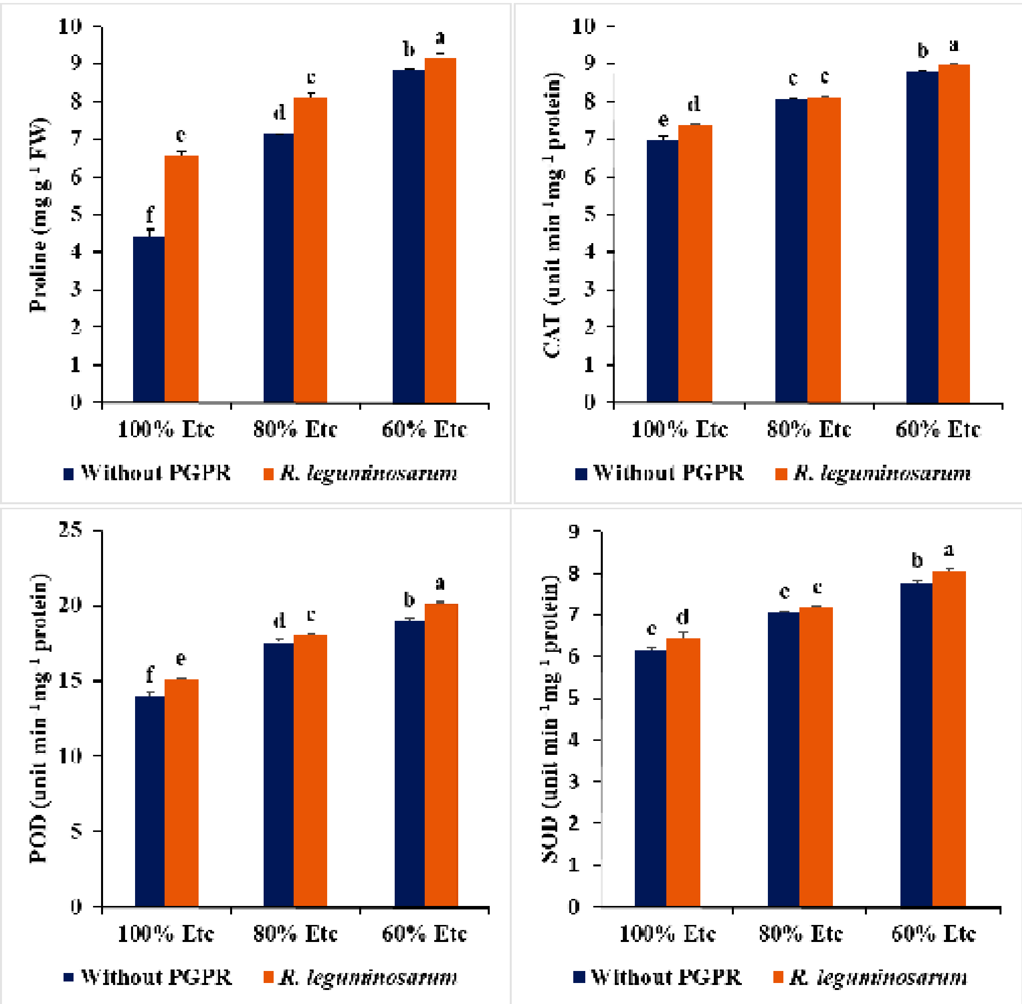

Fig. 5. Effect of Rhizobium leguminosarum bv. Phaseoli application on proline content and enzyme activities of catalyze, peroxidase and superoxide dismutase in leaves of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

pressure and cell volume at low water potential, which is important for maintaining metabolic activities (Wu et al., 2014 and Abid et al., 2016).

Antioxidant Enzyme Activity

Under drought stress conditions, it is well known that plants synthesize de novo enzymes and activate enzymatic antioxidant machinery to protect themselves against overproduction of ROS through the scavenging process (Miller et al., 2010). In our experiment, as shown in Fig. 5, water deficit levels (80 and 60% ET_c) significantly improved the antioxidant enzyme activities (CAT, POD, and SOD) compared with the well-watered condition. In the same manner, Amine-Khodja et al. (2022) found that the activity of the antioxidant enzymes in leaves significantly increased under water-limited conditions. In our study, treating with *Rhizobium leguminosarum* significantly enhanced the activities of these antioxidant enzymes compared with the non-bacterium treatment under the three water irrigation levels (100, 80 and 60 % ET_c). The obtained results are in good accordance with Amine-Khodja et al. (2022) who found that *Rhizobium* enhanced the antioxidant enzymatic activity in the leaves of faba bean to cope with drought stress conditions.

Pod Yield Attributes and WUE

Fig. 6 reveals that pod yield and its components were significantly decreased by increasing the severity of the water deficit levels. Drought stresses diminished pod yield by 27.59 and 58.03% at 80 and 60% ET_c, respectively, in comparison with well-watered conditions. Severe drought stress affected productivity through its strong interference with physiological and biochemical processes. *Rhizobium leguminosarum* application

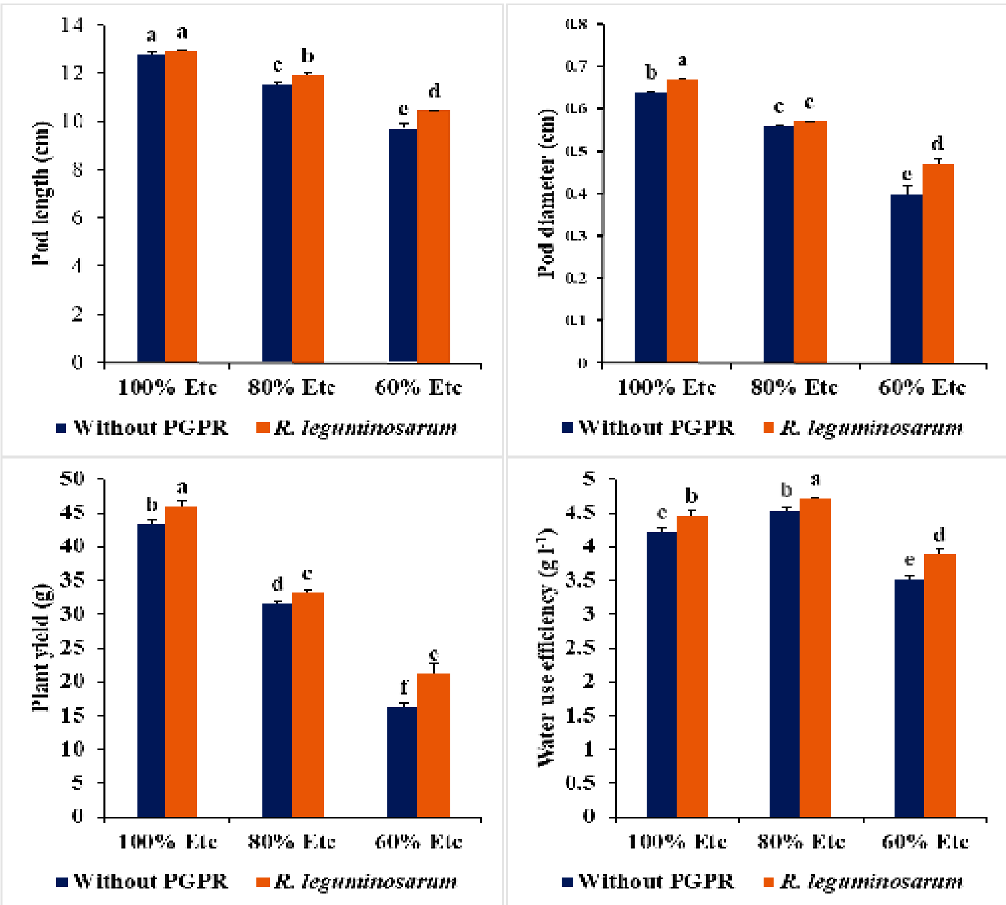

Fig. 6. Effect of Rhizobium leguminosarum bv. Phaseoli application on yield attributes and water use efficiency (WUE) of green bean plants cv. Valentino grown under different water regimes (100, 80 and 60% ETc). Vertical bars represent the standard errors of three independent replicates. Lowercase letters above bars indicate significant differences among the treatments at P≤0.05 (combined analysis of both seasons).

enhanced the pod yield and its components under all water regimes. These increments in yield and its components may be attributed to the fact that *Rhizobium leguminosarum* application enhanced all physiological and biochemical parameters, as obtained from our results. Moreover, the same figure shows that WUE gradually increased when decreasing the water application from 100 to 80% ETc and then significantly decreased under severe drought stress (60% ETc). Where water use efficiency is expressed as the weight of economic fruit yield (g or kg) per unit of consumed water (litter or cubic meter). The achieved results are in accordance with those obtained by Nemeskéri et al. (2018). Again, *Rhizobium leguminosarum* inoculation substantially enhanced WUE compared with the check plants under all water treatments. Similarly, Dashadi et al. (2011) found that inoculation with *Rhizobium* increased water use efficiency in faba beans under water deficiency.

Principal Component Analysis (PCA)

A principal component analysis (PCA) was performed to determine the association between the evaluated parameters and the *Rhizobium* treatment under different water irrigation levels (Fig. 7). The two principal components were constructed and reflected the highest possible variability, approximately 97% (90.5% by PC1 and 6.5% by PC2). Both 100 and 80% ET_c were located on the positive side of PCA1, whereas 60% of ETc was located on the negative side. The obtained results demonstrated that the 23 parameters evaluated could be divided into two clusters: the first cluster contains 19 parameters, including vegetative growth parameters, nutrient contents, physiological traits, yield components and WUE, while the second cluster contains 4 parameters, including proline accumulation and enzymatic antioxidants. In addition, it was observed that there were strong negative correlations between

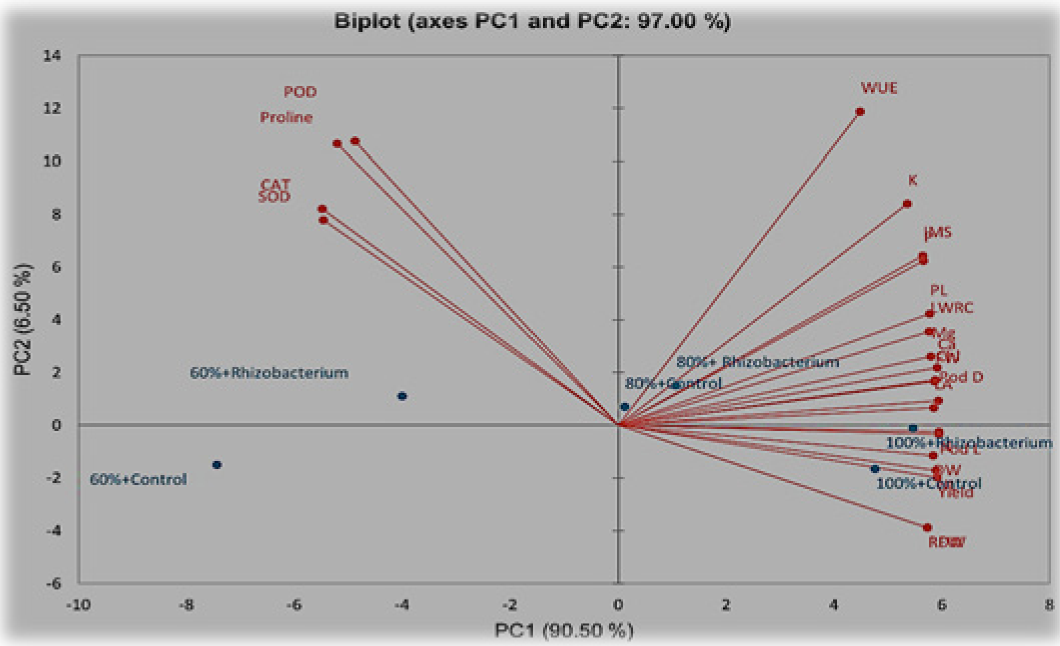

Fig. 7. A principal component analysis (PCA) of the effect of Rhizobium leguminosarum application on vegetative growth, mineral contents, physiological, and biochemical parameters of green bean plants cv. Valentino grown under different water irrigation levels (100, 80, and 60% of ETc). Each variable is represented by an arrow, and the longer its length, the greater its contribution to a given component. The angle between arrows indicates the degree of correlation among variables, the smaller the angle, the higher the correlation.

Abbreviations: PL, plant length; NL, number of leaves/plant; LA, leaf area; SFW, shoot fresh weight; RFW, root fresh weight; SDW, shoot dry weight; RDW, root dry weight; N, N content; P, P content; K, K content; Ca, Ca content; Mg, Mg content; LWRC, leaf relative water content; MSI, leaf membrane stability; Proline, proline content; CAT, catalyze activity; POD, peroxidase activity; SOD, superoxide dismutase activity; Pod L, pod length; Pod D, pod diameter; Yield, plant yield; WUE, water use efficiency.

vegetative growth parameters, physiological traits, and yield attributes on the one hand and proline and antioxidant enzyme activities on the other hand under drought stress conditions.

Conclusion

Currently, the application of plant growth-promoting rhizobacteria is widely used as a good agricultural and eco-friendly practice to achieve sustainable agricultural production and to modulate the plant's response to abiotic stress conditions. The current study revealed that the drought stress (80 and 60% ET_c) was extremely harmful to the uninoculated green bean plants. *Rhizobium leguminosarum* bv. *Phaseoli* had notably reduced the deleterious effect of drought stress by increasing the vegetative growth parameters, leaf chlorophyll content as SPAD readings, physiological biomarkers (LRWC and LMSI), yield components, and inducing the accumulation of proline and antioxidant enzyme activities. Application of *Rhizobium leguminosarum* bv. *Phaseoli* can be recommended as a highly promising strategy under water deficit stress for improving the growth and productivity of green bean plants.

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Conflict of interests

The authors declare that they have no competing interests.

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بكتريا الريزوبيم حسنت من تحمل نباتات الفاصوليا الخضراء لإجهاد الجفاف من خلال تحسين العمليات الفسيولوجية والبيوكيميائية

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بسبب الإحتباس الحراري وتغير المناخ، يعتبر الجفاف أحد الإجهادات غير الحيوية الرئيسية والتي تسبب العديد من التغيرات المورفولوجية والفسيولوجية والبيوكيميائية التي تحد من نمو النباتات وإنتاجيتها. وقد وجد في العديد من الدراسات أن البكتريا المشجعة لنمو النبات تحسن من تحمل النباتات لظروف الجفاف. وبناءاً على ذلك فقد أجريت هذه الدراسة لتقييم دور *Rhizobium leguminosarum* bv. *Phaseoli* في تخفيف الآثار الضارة لنقص المياه (80 و 60 ٪ من البخر نتح المقدر للمحصول) على نمو وإنتاجية نباتات الفاصوليا الخضراء. كان تصميم التجربة قطاعات كاملة العشوائيه بثلاث مكررات. وأظهرت النتائج المتحصل عليها أن زيادة شدة نقص المياه أدت إلى انخفاض واضح في صفات نمو النبات، محتوى الأوراق من العناصر، قراءات درجة إخضرار الأوراق، محتوى الماء النسبي بالاوراق، دليل ثبات الأغشية بالاوراق ومكونات المحصول، كما أدت إلى حدوث زيادة في تراكم البرولين، والنشاط الإنزيمي لإنزيمات الكتاليز والبيروكسيديز والسوبرأوكسيديز. كما أدت إضافة *Rhizobium leguminosarum* إلى تحسن كبير في جميع قياسات النمو والمحصول، قراءات درجة الإخضرار، محتوى الماء النسبي، دليل ثبات الأغشية، محتوى البرولين، ونشاط إنزيمات مضادات الأكسدة. من النتائج المتحصل عليها يمكن استنتاج أن إستخدام بكتريا *Rhizobium leguminosarum* تعتبر إستراتيجية واعدة ومستدامة لتخفيف الآثار السلبية لإجهاد الجفاف وتحسين نمو وإنتاجية نباتات الفاصوليا الخضراء في فترة تغير المناخ المستقبلية.