

Stress Mitigation of Salinity-Induced Growth Inhibition In Mungbean Through Association With the Endophytic Fungus *Stemphylium solani*

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KEY WORDS

Salinity, mung bean, *Stemphylium solani*, photosynthetic pigments, ion homeostasis, antioxidant enzymes, endogenous IAA, flavonoids.

ABSTRACT

The purpose of this research was to assess the behavior of the endophytic fungus (*Stemphylium solani*) in conferring salt tolerance in mung bean, with respect to alterations in the plant's ionic balance, fluctuations in endogenous IAA concentration, antioxidant enzyme activities, physiological and biochemical attributes, and overall seedling growth performance. A completely randomized pot experiment was conducted to assess the effect of the endophytic fungus *Stemphylium solani* on mung bean seedlings grown under control and salinity (150 mM NaCl) conditions. After 35 days of treatment, plant growth, physiological, biochemical, antioxidant, and ionic characteristics were evaluated. Analysis of the data revealed that salinity reduced seedling growth (plant height, root length, number of leaves, fresh biomass, and dry biomass), photosynthetic pigments (chlorophyll a, chlorophyll b, and total chlorophyll), endogenous IAA, total carbohydrates, total proteins, total lipids, and essential mineral nutrients (K, Ca, Mg, N, and P). On the other hand, salinity increased chlorophyll a/b ratio, phenols, tannins, flavonoids, proline, lipid peroxidation, antioxidant enzyme activities (ascorbate peroxidase and catalase), Na and Cl accumulation, and Na/K and Na/Ca ratios. In this study, the endophytic fungus exhibited promising growth promoting activity under both normal and saline conditions. The results showed that *Stemphylium solani* improved plant growth, biomass, chlorophyll contents, total carbohydrates, total proteins, flavonoids, antioxidant enzyme activities, endogenous IAA, and the uptake of K, Ca, Mg, N, and P, while reducing lipid peroxidation, phenols, tannins, Na and Cl accumulation, and Na/K and Na/Ca ratios under salinity stress. The present study concludes that the association of *Stemphylium solani* confers salt tolerance in mung bean and suggests its potential use as a bioinoculant for improving crop productivity under saline environments of Khyber Pakhtunkhwa (KPK).

INTRODUCTION

Excessive accumulation of soluble salts, known as soil salinization, is currently considered a serious threat to agricultural lands worldwide and directly undermines soil quality and value (Shokri et al., 2024). It is predicted that 20 percent of total cultivated land and 33 percent of irrigated agricultural land worldwide are saline, with this figure rising to 30 percent by 2050 if the current trend of salinization continues (Kumar and Sharma, 2020). So, agricultural productivity will decrease due to the reduction in cultivable land. Plants are important in the food chain and are among the first to be affected by this serious problem. This factor alters plant basic physiology and biochemistry, including photosynthesis, water absorption, osmotic stress, homeostasis and ion distribution within the cell, resulting in reduced growth and productivity (Sarkar and Sadhukhan, 2023).

Pulses are a protein-rich source in dietary supplements and are important in meeting the populations requirements. *Vigna radiata* L. (mung bean) is a short-growing, diploid crop with 22 chromosomes, cultivated worldwide for its protein-rich edible seeds (Chandora and Rana, 2023). This crop belongs to the genus *Vigna*, which has over 150 species native to Africa and Asia, with the greatest genetic diversity in tropical Asian countries. A total of 129,903 mung bean accessions are held ex situ at various institutes worldwide (Nair et al., 2023). Mung bean is a self-pollinated crop, and its productivity is severely reduced under abiotic stresses (Singh et al., 2022). It is a salt-sensitive crop, and its productivity is also reduced under salt stress. The adverse effect of salt on grain production is greater during the reproductive stage than at any other life-cycle stage (Le et al., 2021).

Different strategies have been adopted to enhance plant growth in a saline environment; one biological approach, the use of endophytes, has been established. According to Madouh and Quoreshi (2023), in different arid and semi-arid zones, mycorrhizal fungal associations have been suggested to play an important role in conferring salt tolerance in various plants. The tolerance strategy of plants to salinity is based on biochemical, molecular, and cellular adaptations (Rahman et al., 2021). Different plant species strongly influence endorhiza development and the rhizosphere microbiome (Yue et al., 2023). Different plant growth-promoting rhizobacteria (PGPR) exerted direct growth-stimulating effects on plant growth and development after association by releasing different phytohormones (IAA, cytokinin, glycine-betaine, etc.), soluble phosphates and

iron, thereby increasing the plant's tolerance to saline conditions (Sen et al., 2024).

Endophytes also secrete various secondary metabolites (flavonoids, phenols etc.) that help in improving plant growth under salt stress (Slama et al., 2023). Endophytic fungi grow in the interior of plants without causing disease, forming symbiotic relationship with the host plant. Fungi help plants grow by producing phytohormones that influence growth processes, thereby enhancing nutrient uptake, antioxidant capacity, osmoregulation, and ionic homeostasis under adverse environmental conditions (Alam et al., 2021). Various fungal (*Trichoderma*, *Piriformospora*, *Penicillium*, *Aspergillus*, and *Fusarium*) species have been reported to enhance the salinity tolerance of legumes by alleviating oxidative stress and improving nutrient uptake (Chandra et al., 2020). The genus *Stemphylium* (Pleosporaceae, Pleosporales) includes species that are pathogenic, saprophytic and endophytic. Several species have been recognized as pathogens of plants but recently a few strains have been identified as beneficial endophytes that promote plant growth under abiotic stresses (Chande et al., 2024). The study conducted by Husna et al. (2022) showed that *Stemphylium solani* increases plants resistance to chromium stress by improving growth, phytohormone production, antioxidant defense and stress responsive metabolite levels, which reduces heavy metal toxicity. However, information regarding the role of *Stemphylium solani* in enhancing salinity tolerance in mung bean remains limited. Therefore, the present study was undertaken to investigate its potential as a beneficial endophyte for improving plant performance under saline conditions. In this regard, the current study postulated that the presence of the endophytic fungus (*Stemphylium solani*) improves salinity tolerance in mung beans. For this purpose, the present study aimed to assess the impact of *Stemphylium solani* inoculation on plant growth, physiological and biochemical responses, endogenous IAA content, antioxidant defense and ionic homeostasis under salt stress conditions.

MATERIAL AND METHODS *Stemphylium solani* purification and spore suspension preparation

Stemphylium solani (PWR) culture used in this study was obtained from the PMI (Plant-Microbe Interaction) laboratory, Department of Botany, Abdul Wali Khan University Mardan (AWKUM). The fungus was purified by repeatedly subculturing on PDA (potato dextrose agar) and incubating for 2 weeks at 25 °C to produce sufficient spores (conidia). For spore dispersion purposes, mycelia along with spores were transferred to the PDA media in a sterile conical tube (50 ml) using a sterile blade (No. 21). Then, 20 mL of distilled water was added to the tube and vortexed for 5 minutes. Then filter the suspension through filter paper (Whatman No. 2). The final concentration of the spore suspension (5×10^7 spores/mL) was adjusted with distilled water and used in this study.

Characterization of *Stemphylium solani*

After seven days of incubation, the fungal culture was filtered and subsequently centrifuged at 3000 rpm for 10 min to obtain a clear supernatant. The resulting fungal filtrate was used to quantify fungal-derived hormones and metabolites. Indole-3-acetic acid (IAA) content was determined using the Salkowski colorimetric assay, as described by Benizri et al. (1998). Salicylic acid concentration in the fungal filtrate was measured spectrophotometrically according to the procedure of Warriar et al. (2013). The total phenolic content was quantified using the method of Malick and Singh (1980), while total flavonoid content was determined by the aluminum chloride colorimetric assay described by Mervet et al. (2009). Total protein was extracted and quantified according to the Lowry et al. (1951). Total soluble sugars were estimated using a modified phenol-sulfuric acid method as described by Khani and Heidari (2008). Total lipid content in the fungal filtrate was determined according to the method of Van Handel (1985).

Microscopy of the pure fungal colonies

Pure fungal colonies were examined microscopically to study their structural characteristics. A small portion of actively growing mycelium was aseptically removed from the culture and placed on a clean glass slide containing a drop of sterile distilled water. Lactophenol-cotton blue was used as both a staining and mounting medium to enhance visualization of fungal structures. A coverslip was gently placed over the specimen, and slight pressure was applied to evenly spread and flatten the material. The preparation was first observed under low magnification and subsequently under higher magnifications (40× and 100×) using a compound light microscope. Morphological features of the hyphae and spores, including shape, arrangement, and septation, were carefully examined and recorded.

Experimental layout

An experiment was designed to assess the performance of *Stemphylium solani* (PWR) inoculated onto mung bean plants by observing plant growth and biochemistry. An experimental setup employed a Completely Randomized Design (CRD) following plant inoculation with *Stemphylium solani* (PWR). Seed collection of mung bean (Var. Ramzan) was done from the Agriculture Research Institute (ARI), Tarnab, Peshawar. Viability test performed before the germination process. Seed sterilization was performed with mercuric chloride (0.1%) for 60 seconds, followed by three washes with distilled water. The experimental set-up comprises a total of 12 plastic pots (8.5 cm in diameter and 12.5 cm deep) with a basal outlet (to permit leaching) and filled with 300 grams of sandy loam soil. Soil samples were taken and tested for various physical and chemical parameters before the pots were filled (Table 1). The disinfected seeds were germinated, and at the seedling stage, a spore suspension of *Stemphylium solani* was applied at 1ml/g to the required set. Then, after 5 days, a sodium chloride (NaCl) solution at 150 mM, with an equal volume of tap water in the control sets, was applied 2 times/week. The 150 mM NaCl concentration was chosen because it was found to cause moderate salinity stress in mungbean which led to physiological and biochemical changes while allowing plant growth. Hence, this concentration is found to be suitable for the stress relieving ability of endophytic fungi under controlled conditions (Ali et al., 2021). There were four treatment sets in this experimental design, each repeated three times with five plants per pot.

Set-I: Mung-bean seedlings were irrigated with tap water (0 mM NaCl).

Set-II: Mung bean seedlings were irrigated with a 150 mM NaCl solution.

Set-III: Mung-bean seedlings were inoculated with spores of *Stemphylium solani* (PWR) and irrigated with tap water (0 mM NaCl).

Set-IV: Mung-bean seedlings were inoculated with spores of *Stemphylium solani* (PWR) and irrigated with 150 mM NaCl solution.

After 35 days, the experiment was terminated, and the mung bean plants were harvested. For each harvested plant, the root and shoot were carefully separated and washed with tap water to remove soil particles. The fresh and dry weight of the shoot and root was measured using an electronic balance. Dry weight was measured from the same parts after drying in the oven for 72 hours at 60 °C.

Analysis of Photosynthetic Pigments, Proline, and Primary Metabolites

The contents of photosynthetic pigments, proline, and primary metabolites (carbohydrates, proteins, and lipids) in the experimental plants were quantified as described by Ali et al.

(2021).

Estimation of Secondary Metabolites and Indole-3-Acetic Acid (IAA)

The concentrations of secondary metabolites, including phenols, flavonoids, and tannins, as well as indole-3-acetic acid (IAA), were determined according to the methods reported by Ali et al. (2022).

Assessment of Lipid Peroxidation and Antioxidant Enzyme Activities

Lipid peroxidation levels and the activities of antioxidant enzymes (catalase and ascorbate peroxidase) were measured in the experimental plants using the protocols described by Gul et al. (2023).

Different Minerals Determination

Plant samples were collected to test for several cations (K^+ , Na^+ , Mg^{2+} , and Ca^{2+}). The ash weight was calculated using 0.5 grams of dried plant material. The ash was mixed with 50 mL of deionized water, and the solution was diluted with deionized water for cation analysis. An atomic absorption spectrophotometer was used to measure the concentration of cations in various samples.

Determination of chloride and nitrogen

Chloride concentration was measured by automated flow analysis following the procedure of Asch et al. (2022). Total nitrogen was analyzed by the Kjeldahl procedure, as described by Kirk (1950).

Statistical Analysis

Using SPSS (Ver. 21), data on various factors were analysed using two-way analysis of variance (ANOVA). At the $P < 0.05$ level, the means of the different treatments were compared using Duncan's multiple-range test (DMRT).

RESULTS

Characterization of *Stemphylium solani*

Culture filtrate analysis of *Stemphylium solani* showed a considerable level of IAA (32.52 µg/ml), salicylic acid (284.67 µg/ml), flavonoids (111.31 µg/ml), total phenols (121.71 µg/ml), proteins (76.12 µg/ml), lipids (6.08 µg/ml) and sugars (188.79 µg/ml).

Seedling establishment

Present results indicate that salinity stress applied at 150 mM caused significant ($P \leq 0.05$) inhibition in plant height (11.667 cm in 150 mM NaCl / 18.667 cm in control), root length (2.633 / 3.767 control), number of leaves (2.997 / 3.368 control), fresh biomass (0.240 / 0.385), and dry biomass (0.156 / 0.284 control) while comparing with control plants (Table 1).

Association of PWR with mung bean under normal and stressed conditions caused significant ($P \leq 0.05$) improvements in the studied attributes. Under saline conditions, PWR inoculation improved plant height (16.667 cm), root length (3.433 cm), number of leaves (3.643), fresh biomass (0.307 g), and dry biomass (0.207 g) compared with the uninoculated salt stressed plants.

Table 1. Physicochemical properties of the experimental soil.

Physical Characteristics	
Property	Value
Texture	Sandy loam
Silt	11.80%
Clay	14.50%
Sand	73.60%
Chemical Characteristics	

Property	Value
pH	7.6
Organic matter	1.46%
Organic carbon	4.22%
Carbonates	1.36 meq L ⁻¹
Bicarbonates	2.70 meq L ⁻¹
Chlorides	1.25 meq L ⁻¹
CEC	4.2 dS m ⁻¹
ECe	1.35 dS m ⁻¹

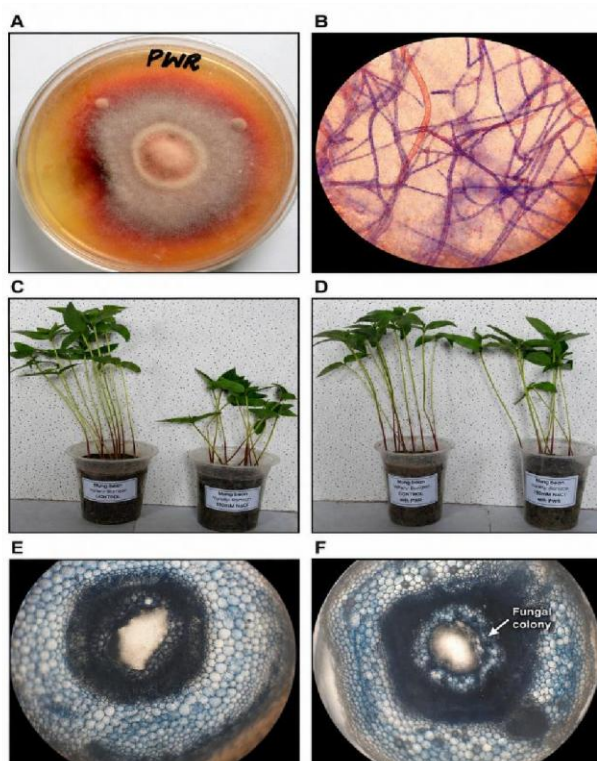
Figure 1. Morphological characteristics of *Stemphylium solani* (PWR) and its interaction with mung bean. (A) Fungal colony, (B) fungal hyphae, (C) uninoculated plants under control and 150 mM NaCl stress, (D) PWR-inoculated plants under control and 150 mM NaCl stress, (E) root cross-section of uninoculated plants, and (F) root cross-section of PWR-colonized plants. **Photosynthetic apparatus activity**

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Table 2. Effect of *Stemphylium solani* (PWR) inoculation on plant height, root length, number of leaves, and fresh and dry biomass in mung bean plants supplemented with 150 mM NaCl.

Treatment	Plant Height (cms)	Root Length (cms)	Leaves (numbers)	Fresh Biomass (gms)	Further, the association of PWR with mung bean under normal and stressed conditions resulted in significant ($P \leq 0.05$) improvement in the studied attributes. Under saline conditions, PWR inoculation improved chlorophyll a (3.26 mg/g), chlorophyll b (1.92 mg/g), total chlorophyll (5.17), chlorophyll a/b ratio (1.71), and total carotenoids (2.42 mg/g) compared with the uninoculated salt stressed plants.
Control	18.6±0.088ab	3.7±0.033c	3.3±0.088b	0.385±0.003ab	
150mM NaCl	11.6±0.176c	2.6±0.033b	2.9±0.067c	0.240±0.004c	
PWR	20.3±0.203a	4.0±0.044a	3.6±0.058a	0.497±0.001a	
NaCl + PWR	16.6±0.033b	3.4±0.088c	3.6±0.033a	0.307±0.005bc	
Probability Level (Salt × PWR)	$P < 0.001$	$P < 0.001$	NS	$P < 0.001$	

Values are presented as mean ± SE (n = 3). Different lowercase letters within each column indicate significant differences among treatments according to Duncan's Multiple Range Test (DMRT) at $P \leq 0.05$. Probability levels represent the Salt × PWR interaction obtained by two-way ANOVA.



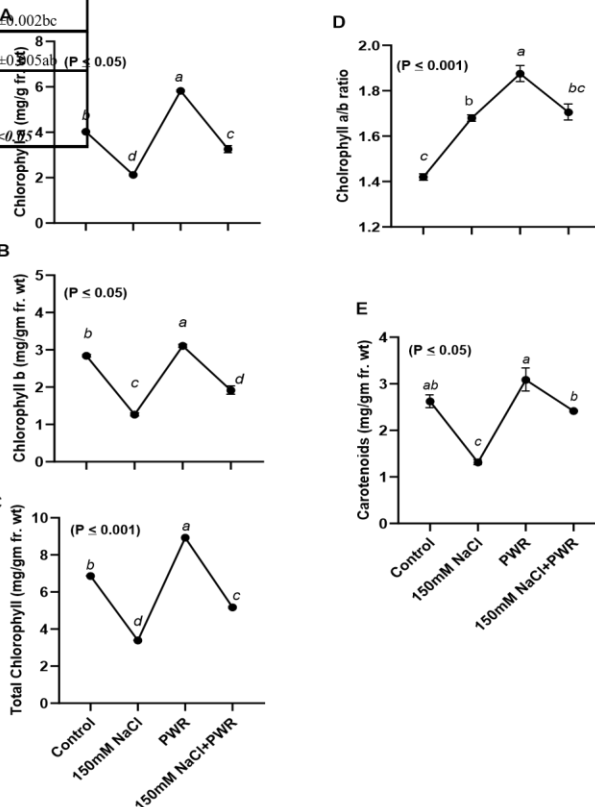
Data of the present investigation indicate that salinity stress applied at 150 mM caused significant ($P \leq 0.05$) inhibition in chlorophyll a (2.13 mg/g FW in 150 mM NaCl / 4.03 in control), chlorophyll b (1.27 / 2.84 control), total chlorophyll (3.39 / 6.87 control), while exhibiting an increase in chlorophyll a/b ratio (1.68 / 1.42 control) and a reduction in total carotenoids (1.31 / 2.62 control) as shown in Figure 2.

Figure 2. Effect of *Stemphylium solani* (PWR) on mung bean under control and 150 mM NaCl stress. (A) chl a, (B) chl b, (C) total chl, (D) chlorophyll a/b ratio (E) carotenoids. Values are mean ± SE (n = 3). Different lowercase letters indicate significant differences (DMRT, $P \leq 0.05$). Salt × PWR interaction significance (two-way ANOVA) is shown for each parameter.

Total Carbohydrate, proteins, lipids and proline content

Figure 3 showed that application of 150 mM NaCl caused significant ($P \leq 0.05$) reductions in total carbohydrates (30.11 in 150 mM NaCl / 44.26 in control), total proteins (0.532 / 1.610 in control), and total lipids (0.197 / 0.379 in control), while proline content increased (0.057 / 0.028 in control) compared with the control plants.

Association of PWR with mung bean under normal and stressed conditions caused significant ($P \leq 0.05$) improvements in the studied attributes. Under saline conditions, PWR inoculation increased total carbohydrates (37.93 mg g⁻¹ FW), total proteins (1.478



mg g⁻¹ FW), total lipids (0.290 mg g⁻¹ FW), and proline (0.094 μmol g⁻¹ FW) compared with the uninoculated salt-stressed plants.

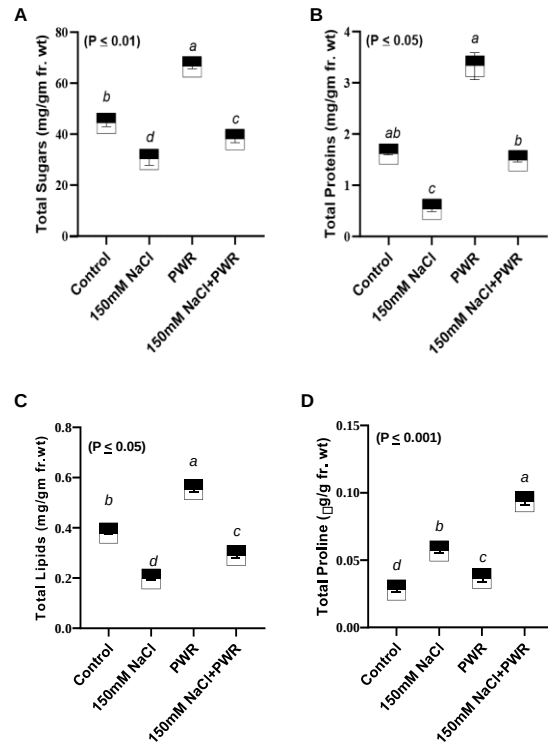


Figure 3. Effect of *Stemphylium solani* (PWR) on mung bean under normal and 150 mM NaCl stress. (A) Total carbohydrates, (B) total proteins, (C) total lipids (D) proline. Values are mean $\pm$ SE ($n = 3$). Different lowercase letters indicate significant differences (DMRT, $P \leq 0.05$). Salt $\times$ PWR interaction (two-way ANOVA) is shown for each parameter.

Secondary metabolites

Current data illustrated that salinity stress applied at 150 mM caused significant ($P \leq 0.05$) increases in total phenols (265.11 in 150 mM NaCl / 140.89 in control), total flavonoids (1.575 / 0.881 in control), and total tannins (93.10 / 81.71 in control) compared with the control plants (Figure 4).

Moreover, the association of PWR with mung bean under normal and stressed conditions caused significant ($P \leq 0.05$) changes in the studied attributes. Under saline conditions, PWR inoculation reduced total phenols (167.17 mg g^{-1} FW) and total tannins (74.65 mg g^{-1} FW), while increasing total flavonoids (2.463 mg g^{-1} FW) compared with the uninoculated salt-stressed plants.

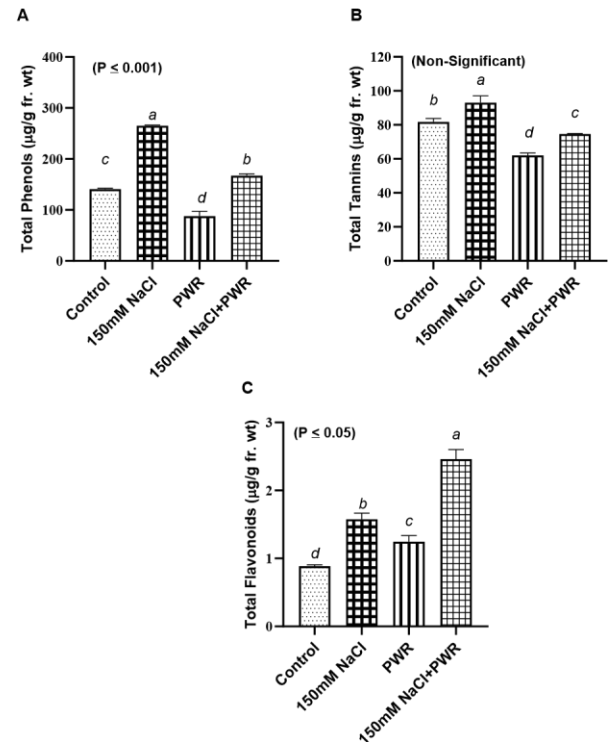
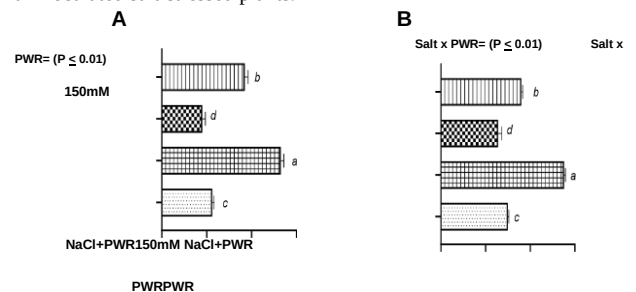


Figure 4. Effect of *Stemphylium solani* (PWR) on mung bean under control and 150 mM NaCl stress. (A) Total phenols, (B) total tannins, and (C) total flavonoids. Values are mean $\pm$ SE ($n = 3$). Different lowercase letters indicate significant differences (DMRT, $P \leq 0.05$). Salt $\times$ PWR interaction (two-way ANOVA) is shown for each parameter.

Membrane Lipid peroxidation, Antioxidant enzymes and IAA level

Regarding the response to 150 mM NaCl, Figure 5 showed that salinity stress caused significant ($P \leq 0.05$) increases in lipid peroxidation (0.053 in 150 mM NaCl / 0.023 in control), catalase (551.62 / 300.03 in control), and ascorbate peroxidase (78.51 / 56.93 in control), while endogenous IAA decreased (0.468 / 0.691 in control) compared with the control plants.

Moreover, association of PWR (*Stemphylium solani*) with mung bean under normal and stressed conditions caused significant ($P \leq 0.05$) changes in the studied attributes. Under saline conditions, PWR inoculation reduced lipid peroxidation (0.037 nmol g^{-1} FW), and catalase (360.15 U mg^{-1} protein), while increasing ascorbate peroxidase (122.25 U mg^{-1} protein) and endogenous IAA (0.602 μg g^{-1} FW) compared with the uninoculated salt-stressed plants.



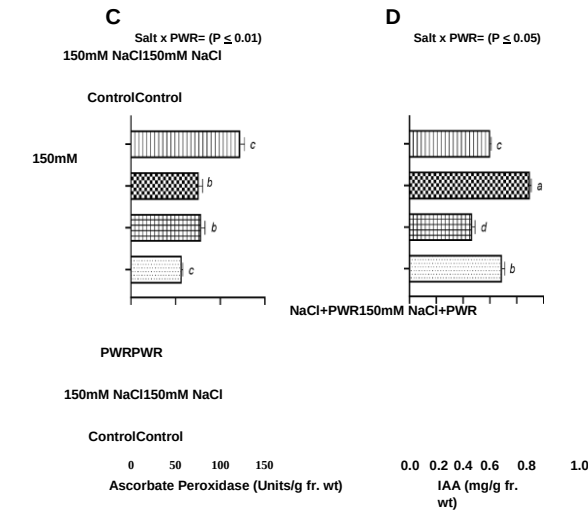


Figure 5. Effect of *Stemphylium solani* (PWR) on mung bean under control and 150 mM NaCl stress. **(A)** Lipid peroxidation (MDA), **(B)** catalase activity, **(C)** ascorbate peroxidase (APX), and **(D)** endogenous IAA. Values are mean ± SE (n = 3). Different lowercase letters indicate significant differences (DMRT, P ≤ 0.05). Salt × PWR interaction (two-way ANOVA) is shown for each parameter.

Ions Concentration

Current data illustrated that salinity stress applied at 150 mM caused significant (P ≤ 0.05) increases in sodium (72.75 in 150 mM NaCl / 9.00 in control), chloride (42.98 / 5.20 in control), Na/K ratio (6.418 / 0.596 in control), and Na/Ca ratio (6.188 / 0.513 in control), while potassium (11.40 / 15.15 in control), calcium (10.85 / 17.65 in control), magnesium (6.25 / 8.95 in control), nitrogen (9.90 / 31.60 in control), phosphorus (2.20 / 4.55 in control) significantly decreased compared with the control plants (Figure 6).

Moreover, the association of PWR (*Stemphylium solani*) with mung bean under both normal and stressed conditions caused significant (P ≤ 0.05) changes in the attributes studied. Under saline conditions, PWR inoculation reduced sodium (21.00 mg g⁻¹ DW), chloride (36.00 mg g⁻¹ DW), Na/K ratio (0.827), and Na/Ca ratio (1.964), while increasing potassium (25.40 mg g⁻¹ DW), calcium (12.05 mg g⁻¹ DW), magnesium (9.65 mg g⁻¹ DW), nitrogen (22.30 mg g⁻¹ DW), and phosphorus (3.40 mg g⁻¹ DW) compared with the uninoculated salt-stressed plant.

Control 150mM NaCl PWR 150mM NaCl+PWR

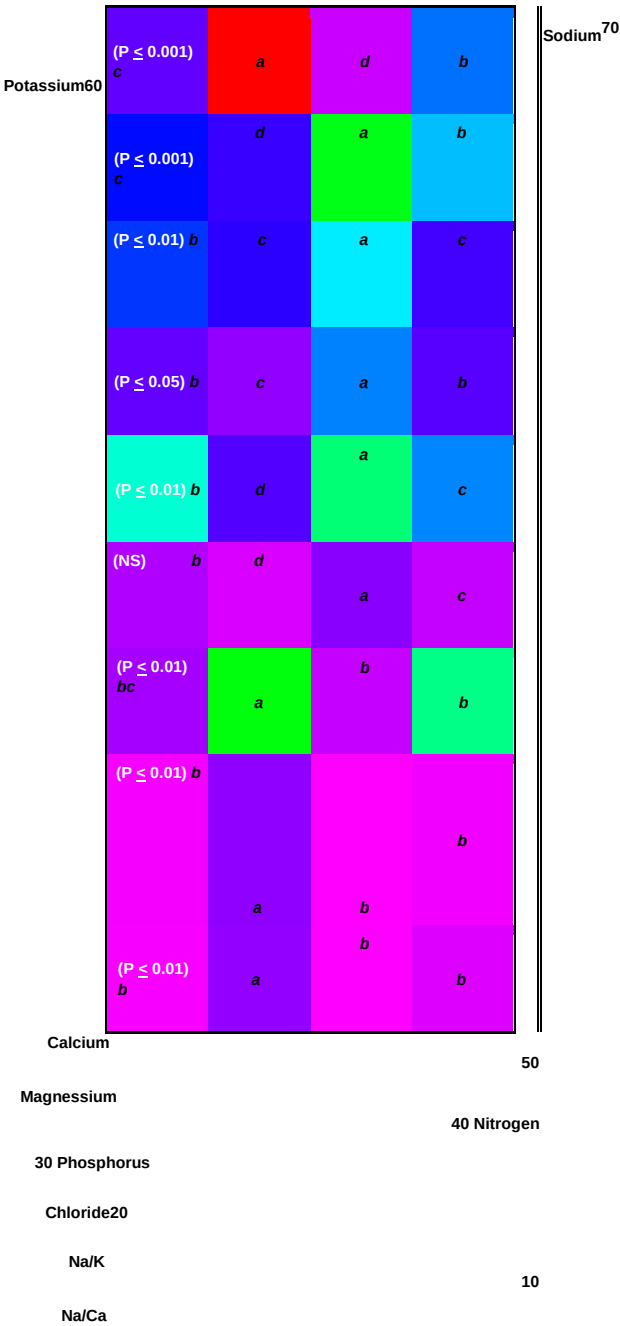


Figure 6. Effect of *Stemphylium solani* (PWR) on mung bean under control and 150 mM NaCl stress. **(A)** Essential and toxic ion concentrations (Na, K, Ca, Mg, N, P, Cl) and ionic ratios (Na/K and Na/Ca). Different lowercase letters indicate significant differences (DMRT, P ≤ 0.05). Salt × PWR interaction (two-way ANOVA) is shown for each parameter.

DISCUSSION

Stress reduces leaf number/plant and total leaf area, a common pattern across plant species (Mehmood et al., 2025). Present results indicate that salinity stress (150 mM NaCl) caused significant reductions in plant height, root length, number of leaves, fresh biomass, and dry biomass compared with the non-saline control plants (Table 2). Shoot length decreases after salt

exposure in a variety of plant species, primarily due to specific ion toxicity, and osmotic stress reduces plant growth (Shoukat et al., 2020). Longterm salt exposure limits root absorption of water and nutrients, and directly injures plant cells due to harmful ion accumulation, leading to reduced plant growth. As a result of a decrease in the number of elongated cells and the rate at which they elongate, salt stress causes a loss in leaf growth (Rodríguez et al., 2023). Cell wall characteristics, leaf turgor, and reduced total leaf area are affected by exposure to saline media, resulting in a lower photosynthetic rate. Biomass loss increased with salinity, which is understandable given the disruptions in physiological and metabolic activity that occur in saline environments. The reduction in biomass resulting from salinity is attributed to a reduction in the number of leaves/ plant and in leaf area. The dry matter content of plants is considered a functional unit that is used to evaluate the plant's resource acquisition and utilization strategy (Hu et al., 2024).

Association of the fungal isolate (*Stemphylium solani*) with mung bean under normal and stressed conditions improved plant height, root length, number of leaves, fresh biomass, and dry biomass under both normal and saline conditions (Table 2). According to Han et al. (2024), in comparison to endophyte-colonized poplar seedlings, the rate of fine root respiration increased in nonendophytic colonized poplar seedlings in saline conditions. In saline environments, symbiotic fungi within plant tissues help maintain metabolic balance by keeping root respiration from rising excessively. This controlled respiration supports more efficient carbon utilization, allowing plants to invest in growth while simultaneously enhancing their tolerance to stress conditions. Conversely, elevated salinity in irrigation water restricts leaf expansion and disrupts normal plant morphology. It also disturbs the coordination between shoot and root systems, ultimately reducing overall plant performance. Endophytic fungal growth provides salt resistance to host plants through greater biomass production as compared to the non-endophytic colonized plant (Yousefi et al., 2025).

In plants immature leaves accumulate salt which causes salt stress in plants with a long-term negative impact on the photosynthetic process. Carotenoids are pigments that serve as antioxidants and prevent lipids of plasma-membrane from oxidative damage created as a result of salt stress (Kesawat et al., 2023). Present results indicate that salinity stress (150 mM NaCl) caused significant reductions in photosynthetic pigments, including chlorophyll a, chlorophyll b, total chlorophyll, and carotenoids, while increasing the chlorophyll a/b ratio compared with the non-saline control plants (Figure 2). Under high salinity stress, fluctuation in photosynthetic-enzyme activity and reduction in chlorophyll and carotenoids level causes a negative impact on photosynthesis. Reduction in photosynthetic rate occurs as a result of stomatal closure, disruption of photosynthetic electron-chain, and inhibition of different enzymes of Calvin cycle e.g. ribulose-5-phosphate kinase, fructose-1,6-bisphosphatase, phosphoenolpyruvate carboxylase (PECP), glyceraldehyde-3-phosphate dehydrogenase, and Rubisco (Farooq et al., 2025).

Association of the fungal isolate (*Stemphylium solani*) with mung bean under normal and stressed conditions improved chlorophyll a, chlorophyll b, total chlorophyll, and carotenoid contents, while slightly increasing the chlorophyll a/b ratio under salinity stress (Figure 2). Plants employ several protective strategies to prevent damage to their photosystems under excessive light conditions. One key approach involves limiting light absorption and safely dissipating excess excitation energy through non-photochemical quenching, thereby reducing the risk of photoinhibition and structural damage (Ma et al., 2025). However, endophytic colonized plants have a lower non-photochemical quenching, therefore, symbiosis improved photosynthetic efficiency by efficiently converting collected light into chemical energy while lowering non-photochemical quenching (Chougule, 2023).

Different soluble sugars were higher in concentration due to different enzymes activities which help in the regulation of different cellular functions and structures after interaction with other macromolecules. Present results indicate that salinity stress (150 mM NaCl) reduced total carbohydrates, total proteins and total lipid contents compared with the non-saline control plants (Figure 3). Insensitive species, increasing chloride levels can cause an increase in carbohydrate levels in plant tissues or starch breakdown, whereas salt-tolerant species accumulate less starch. The rate of carbohydrate accumulation differs between salt-tolerant species (Peng et al., 2022). Plant surface lipids such as waxes and cutin form an impermeable barrier that decreases water loss and protects against diseases and toxins. NaCl has been shown to modify the composition of the membrane, raising the sterol-tophospholipid ratio in wheat root plasma membranes (Lal and Bhatla, 2023).

Association of the fungal isolate (*Stemphylium solani*) with mung bean under salinity stress increased total carbohydrates, total proteins, and total lipid contents compared with the uninoculated salt-stressed plants (Figure 3). There have been reports that endophytic fungi have been shown a higher level of soluble sugars in plants under stressed environments and sugars attract soil rhizobia by acting as chemo-attractants (Sena et al., 2024). Inoculation with *Piriformospora indica* and *Azotobacter chroococcum* enhanced the C18:3 fatty acid content in the phospholipid fraction of *Silybum marianum* leaves under salinity. This modification in total lipid composition may reflect an endophyte-mediated adaptive response that improves plant tolerance to salt stress (Yaghoubian et al., 2022).

Proline reaccumulation is enhanced by the increased activity of pyrroline-5-carboxylate synthetase (P5CS) and decreased activity of proline dehydrogenase in salt-stressed potato seedlings. Under stress conditions, high levels of cytoplasmic proline help maintain osmotic and ionic balance, and the level of cytoplasmic proline is positively related to plant tolerance to stress conditions (Hosseinifard et al., 2022). Under salinity stress, fungal association promoted total proline accumulation compared with the nonstressed inoculated mung bean plants (Figure 3). Higher accumulation of proline in plants associated with endophytic fungi has been attributed to several physiological adjustments. These include reduced entry of toxic ions into cells, which helps maintain osmotic stability, along with the upregulation and enhanced activity of the enzyme Pyrroline-5-carboxylate synthase (P5CS), a key component of proline biosynthesis. Beyond its role in osmotic adjustment, proline is also widely recognized as an important biochemical marker of stress in plants. When the deleterious effects of salt were mitigated by colonization with the endophytic fungus *Piriformospora indica*, proline deposition was reduced in endophyte-colonized tomato plants (Abdelaziz et al., 2019).

Plants have evolved the ability to produce a wide range of phenolic secondary metabolites that are vital for their interactions with the environment, reproductive strategy, and defense mechanisms, but are not required for main growth and development processes. Present results indicate that salinity stress (150 mM NaCl) caused significant increases in total phenols, total tannins, and total flavonoids compared with the non-saline control plants (Figure 4). Tannins are stored as secondary metabolites in vacuoles within the plant cell, where they protect the other cell components. Tannins are water-soluble phenol derivatives that higher plants produce and accumulate as secondary metabolic products (Al-Khayri et al., 2023). Gallic acid (GA), a chemical found in large amounts in tannin-rich combinations, is thought to influence root formation. Its benefits were found to be mostly connected to its antioxidant and auxin-like activities, as evidenced by an increase in growth and antioxidant defenses in gallic acid-treated roots of salt-stressed plants (Campobenedetto et al., 2021).

Association of the fungal isolate (*Stemphylium solani*) with mung bean under salinity stress reduced total phenols and total tannins, while increasing total flavonoids compared with the uninoculated salt stressed plants (Figure 4). Under salt stress, increased levels of flavonoid and phenolic compounds were found in *T. reesei* and these flavonoids and phenols produced play important roles in several areas of plant life, including plant growth, protection against abiotic stress, plant reproduction and disease resistance. Endophytic fungi and bacteria produce a variety of antioxidant metabolites such as flavonoids, phenolic acids, phenolic terpenoids, tannins, and hydroxyanthraquinones (Hashem et al., 2023).

Increased levels of ROS (reactive oxygen species) generation, DNA, lipids, pigments, proteins, and biological molecules are symptoms of plant stress. Present results indicate that salinity stress (150 mM NaCl) increased lipid peroxidation and enhanced catalase and ascorbate peroxidase activities compared with the non-saline control plants (Figure 5). Osmotic stress, caused by salinity, induces stomatal closure and impairs gas exchange; it ultimately results in reactive oxygen species accumulation, increased lipid peroxidation, and cell membrane damage. The CAT enzyme is in charge of converting hydrogen peroxide to water and oxygen. On the other hand, catalase (CAT) decomposed H_2O_2 , produced in peroxisomes as a result of photo-respiration (Anaya et al., 2025). Ascorbate peroxidase is an important enzyme of the scavenging system working on ROS, and it is involved in enhancing salinealkali tolerance in plants, detoxifying H_2O_2 in various cell compartments, maintaining AsA homeostasis, and balancing the intracellular ROS messenger network (Zhang et al., 2026). Association of the fungal isolate (*Stemphylium solani*) with mung bean under normal and stressed conditions improved the studied parameters. Under salinity stress, fungal inoculation reduced lipid peroxidation, while enhancing catalase and ascorbate peroxidase compared with the uninoculated salt stressed plants (Figure 5). Exposure to saline conditions intensifies oxidative stress in plants, which damages membrane lipids and disrupts their integrity, resulting in increased leakage of ions from the cells (Yu et al., 2020). After NaCl treatment, salt-sensitive plants typically show more severe membrane damage than tolerant ones, reflected by higher levels of lipid degradation. Therefore, the extent of lipid peroxidation is often used as a reliable measure of how effectively plants especially those associated with endophytes can tolerate and adapt to salt stress (Hao et al., 2021).

Plants use phytohormone induction as one of their mechanisms for mitigating abiotic stresses, which improves plant growth and productivity in stressful situations (Singh and Roychoudhury, 2023). Present results indicate that salinity stress applied at 150 mM causes a significant reduction in levels of endogenous IAA as compared to non-saline control plants (Figure 5). The conversion of the active form of IAA to its inactive form through the process of conjugation of IAA with amino acids (e.g. Phe, Ala, and Asp) contributes to IAA homeostasis and conversion process catalyzed by IAA amido synthetase, belonging to GH₃ family (Brunoni et al., 2023). In barley (*Hordeum vulgare*) and *Arabidopsis thaliana* different stresses e.g. high temperature restricts the expression of different genes (*YUC2* and *YUC6*), resulting in the reduction of endogenous auxin level in developing anthers and male sterility. This indicates that a reduction in IAA level in specific is the primary response to environmental changes, such as an increase in temperature, which causes pollen development to be delayed and, as a result, yield to be reduced (Mallick et al., 2022). Association of fungal isolate (*Stemphylium solani*) with mungbean under normal and stressed conditions causes improvement in IAA level. Under stress conditions, fungal association causes a reduction in IAA content compared with

non-stressed inoculated mungbean plants (Figure 5). In plants, under salinity endophytic symbiosis has a favorable effect on the endogenous level of IAA. This effect is likely due to their ability to supply or influence auxin levels. The auxin-responsive gene *DR5:uidA* was expressed at higher levels in plants associated with endophytes than in noninoculated plants under salinity, indicating improved auxin signaling (Zhang et al., 2025).

Abiotic stress modifies nutrient intake and transport patterns, resulting in drastic alterations in plant growth. The main rivals for nutrients like Ca^{2+} , K^+ , and NO_3^- are the ions Na^+ and Cl^- . The ionic concentration of soil solutions changes under saline circumstances, with an increase in Na^+ and Cl^- ions, particularly (Hailu et al., 2025). Present results indicate that salinity stress (150 mM NaCl) caused significant increases in sodium and chloride concentrations and the Na/K and Na/Ca ratios compared with the non-saline control plants (Figure 6). Ion imbalance is a key negative effect of salinity during the second phase. Sodium ions compete with potassium ions for binding sites, and potassium is essential for the metabolic process in the cytoplasm, such as different enzyme reactions, protein synthesis, and ribosome functions. It has been widely believed that plants that are salt stressed regulate their sodium absorption and transport in order to keep their cytosolic K^+/Na^+ ratios high, which is an important feature for salt tolerance (Fathalli et al., 2025). Present study indicates that salinity stress (150 mM NaCl) markedly decreased the concentrations of potassium, calcium, magnesium, phosphorus, and nitrogen in mung bean plants compared with the non-saline control, indicating disruption of nutrient uptake and ionic homeostasis (Figure 6). Under saline conditions, decreased K uptake might result in decreased plant growth and output. Plants use vacuole compartmentalization to limit the free cytosolic mobility of Na in the cytosol, preventing Na from interfering with the regular functioning of cytosolic enzymes. Both glycophytes and halophytes depend on this process to survive. Na^+/Ca^{2+} interactions are significant under saline environments because Na^+ can displace calcium from its binding sites, resulting in a decrease in calcium availability. Calcium supplementation helps mungbeans to recover from the harmful effects of salt (Khan et al., 2023). Different nutrients serve as a cofactor for different enzymes of carbon metabolism and its fixation in different photosynthetic pigments. Aside from its role in chlorophyll structure and as an enzyme cofactor, magnesium plays a crucial role in plant photosynthate export, which when impaired leads to increased chlorophyll breakdown in Mg-deficient source-leaves, resulting in increased RuBP carboxylase oxygenase activity (Bhatla and Kathpalia, 2023).

Association of the fungal isolate *Stemphylium solani* with mung bean under normal and stressed conditions significantly reduced sodium and chloride concentrations and Na/K and Na/Ca ratios under salinity stress (Figure 6). Fungi and bacteria can both assist plants in maintaining cellular ion homeostasis and stable K^+/Na^+ ratios in their shoots. Under salt stress, plants associated with endophytes generally maintain a lower Na^+/K^+ ratio compared to non-colonized plants. Chen et al. (2021) reported that increasing potassium levels helps preserve this ionic balance, which in turn reduces sodium toxicity in barley plants inoculated with endophytic fungi. Association of the fungal isolate *Stemphylium solani* with mung bean under normal and stressed conditions increased potassium, calcium, magnesium, phosphorus, and nitrogen concentrations compared with the uninoculated plants (Figure 6). Under saline conditions, endophyte-colonized plants often show increased phosphorus accumulation due to improved soil availability, as insoluble phosphates are converted into soluble forms through processes such as acidification, exchange, and chelation. Endophytic fungi can also absorb phosphorus efficiently at low concentrations through high-affinity phosphate transporters (PiPT) (Sun et al., 2025). In

contrast to mycorrhizal associations, in which fungi preferentially recruit ammonium over nitrate from the soil, endophytic interactions preferentially recruit nitrogen from the soil. By increasing magnesium absorption, endophytecolonized plants retain higher chlorophyll concentrations under salt stress; as a result, plastid integrity is preserved and photosynthetic efficiency is increased (Chaudhary et al., 2022).

Conclusion

In the present study, salinity stress adversely affected the growth, physiological, biochemical, and ionic attributes of mung bean, resulting in reduced plant growth and disturbed ion homeostasis. In contrast, inoculation with *Stemphylium solani* improved plant growth, photosynthetic pigments, endogenous IAA, antioxidant enzyme activities, nutrient uptake (K, Ca, Mg, N, and P), and flavonoid accumulation, while reducing lipid peroxidation, Na and Cl accumulation, Na/K and Na/Ca ratios, and excessive phenol and tannin accumulation under saline conditions. Therefore, *Stemphylium solani* can be considered a promising bioinoculant for improving mung bean growth and salt tolerance, with potential applications in crop production on salt affected soils in Pakistan.

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