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# Enhancement of phosphate solubilization by endophytic bacteria under salinity and phosphorus deficiency stress conditions

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## ABSTRACT

Soil salinization and phosphorus (P) deficiency are critical environmental challenges that severely limit global agricultural productivity, particularly in the arid regions of Uzbekistan. Under saline conditions, P is rapidly immobilized, becoming unavailable for plant uptake, which leads to stunted growth and significant yield losses. This study addresses the urgent need for sustainable bio-remediation by evaluating halotolerant endophytic bacteria as effective bio-fertilizers. Several endophytic bacterial strains isolated from native halophytes were screened for their tolerance to extreme salinity (up to 10% NaCl) and their ability to solubilize insoluble phosphates. The most potent isolates, *Pseudomonas putida* KoPr129 and *Bacillus amyloliquefaciens* HAPH2, were biochemically characterized for plant growth-promoting (PGP) traits, including IAA, ammonia, and HCN production. A 6-week greenhouse pot experiment was conducted to validate their efficacy on wheat (*Triticum aestivum* L.) under 150 mM NaCl stress and P-deficient conditions. In vitro assays confirmed that P. putida KoPr129 maintained a robust phosphate solubilization index (FPI 18.16±0.56 mm) even at 10% NaCl. Greenhouse trials demonstrated that inoculation with these endophytes significantly mitigated the negative impacts of combined stress. Specifically, *P. putida* KoPr129 increased wheat shoot length by 9% and more than doubled the total phosphorus uptake (over 130% increase) compared to the non-inoculated stressed control. Biochemical profiling revealed high levels of IAA production in both strains, facilitating enhanced root architecture and nutrient acquisition. Our findings demonstrate that halotolerant endophytes, particularly *P. putida* KoPr129, are superior candidates for the development of effective bio-inoculants. These results provide a promising pathway to restore soil fertility and improve wheat productivity in degraded, saline-alkali landscapes, offering a sustainable alternative to chemical fertilizers.

**Keywords:** Endophytic bacteria, phosphate solubilization, salinity stress, *Pseudomonas putida, Bacillus amyloliquefaciens*, Molybdenum blue.

## INTRODUCTION

Global food security is currently facing unprecedented challenges due to the rapid growth of the human population and the concurrent degradation of agricultural lands caused by environmental changes. Among various abiotic stresses, soil salinity is a primary constraint that severely limits crop productivity worldwide, particularly in arid and semi-arid regions (Gilbert et al., 2010; Zhu et al., 2011; Mamadoliev et al., 2026). Salinity stress not only hinders seed germination and vegetative growth but also significantly reduces the bioavailability of essential macronutrients, most notably phosphorus (P) (Norboyev et al., 2024; Yoneyama et al., 2012).

Phosphorus is a vital element for plant development, involved in energy transfer, photosynthesis, and DNA synthesis. Although total soil phosphorus is often abundant, approximately 60–70% of applied chemical P-fertilizers become rapidly immobilized through adsorption to iron, aluminum, or calcium compounds, making them unavailable for direct plant uptake (Alori et al., 2017). In saline soils, this problem is exacerbated as high salt concentrations further decrease P solubility, forcing farmers to increase chemical fertilizer applications. This practice leads to negative ecological consequences, including soil degradation, groundwater contamination, and the disruption of soil microbial communities.

To address these challenges, ecological engineering strategies have shifted toward the use of Plant Growth-Promoting Rhizobacteria (PGPR) and endophytic bacteria as sustainable alternatives to chemical inputs (Hayat et al., 2010; Mitter et al., 2021). Endophytic bacteria, which colonize internal plant tissues, offer a unique advantage by directly assisting the host plant from within, providing better protection against external stresses. These beneficial microbes facilitate phosphorus uptake through several mechanisms, including the production of organic acids, enzymatic hydrolysis, and proton exchange, which lower the rhizosphere pH and release soluble orthophosphates (Premono et al., 1996; Oteino et al., 2015).

While many phosphate-solubilizing bacteria (PSB) have been identified, their efficiency often declines under high osmotic stress (Sanoeva et al., 2025). Therefore, identifying halotolerant endophytic strains that maintain high phosphate-solubilizing activity under saline conditions is crucial for restoring the productivity of salt-affected ecosystems (Jiang et al., 2018; Alikulov et al., 2022).

Recent advancements in agricultural microbiology (2020–2025) have shifted the focus toward halotolerant endophytes as superior alternatives to traditional rhizospheric PGPR. Unlike rhizobacteria, endophytes are biologically buffered within the host plant's internal tissues, protecting them from the extreme osmotic fluctuations of hypersaline soils (Mitter et al., 2021; Axanbayev et al., 2023). While the role of organic acid secretion in phosphorus (P) mobilization is well-documented, the ability of these microbes to maintain metabolic efficiency under combined salt (up to 10% NaCl) and P-deficiency stress remains a critical knowledge gap in arid-zone agriculture.

The main objective of this study was to evaluate the efficiency of selected halotolerant endophytic bacterial strains, in particular those obtained from the collection of Samarkand State University, in solubilizing insoluble calcium phosphate at different salt concentrations (2% to 10% NaCl) and to determine their effect on the development of agricultural crops. By evaluating their efficiency through qualitative (phosphate solubility index) and quantitative (molybdenum blue method and pH dynamics) analyses, this study aims to create a biological basis for the development of environmentally friendly biofertilizers suitable for the management of saline-alkaline soils.

## MATERIALS AND METHODS

### Bacterial strains and collection

The study utilized a collection of endophytic bacterial strains maintained at the Laboratory of Molecular Biotechnology, Samarkand State University named after Sharof Rashidov. The selected strains have previously demonstrated plant growth-promoting (PGP) traits and were isolated from various xerophytic and halophytic plants (Table 1).

### Media preparation and salinity stress induction

To evaluate phosphate-solubilizing activity under salt stress, modified Pikovskaya (PVK) solid medium and PSB were used (David et al., 2009). The media composition per liter of distilled water was: Glucose – 12.0 g; $Ca_3(PO_4)_2$ – 5.0 g; Tryptone – 2.0 g; $(NH_4)_2SO_4$ – 0.5 g; $MgSO_4 \cdot 7H_2O$ – 0.3 g; $MnSO_4$ – 0.03 g; $FeSO_4 \cdot 7H_2O$ – 0.03 g; Agar (for PVK) – 15.0 g. To simulate salinity stress, NaCl was added to the media at concentrations of 2%, 5%, and 10%. The final pH was adjusted to 7.0, and media were sterilized at 121 °C for 15 minutes.

**Table 1.** Characterization of endophytic bacteria collection strains

| Strain name | Gene bank account number | Biochemical characterization* | | | | Isolated plant | References |
|---|---|---|---|---|---|---|---|
| | | Cat. | Prot. | IAA | $NH_3$ | | |
| Bacillus pumilus KoPr113 | ON567220 | + | + | + | + | *Bassia prostrata* (L.) Beck | Axanbayev et al., 2022 |
| Priestia aryabhattai KoPr118 | ON567221 | + | + | + | + | | |
| *Pseudomonas putida* KoPr129 | ON567222 | + | - | ++ | + | | |
| *Bacillus subtilis* CrEw1018 | ON567361 | + | + | + | + | *Krascheninnikovia ceratoides* (L.) Gueldenst. | Akramov et al., 2023 |
| *Bacillus amyloliquefaciens* HAPH2 | MZ443975 | + | + | ++ | + | *Haloxylon ammodendron* (C.A.Mey.) Bunge ex Fenzl | Alikulov et al., 2023 |

**Note:** *Cat. – catalase activity; Prot. – protease activity; IAA – indole-3-acetic acid production; $NH_3$ – ammonia production. Scoring: (+) positive reaction; (-) negative reaction; (++) high metabolic activity.

### Qualitative assessment of phosphate solubilization

Bacterial strains were inoculated onto PVK agar plates and incubated at 28–30 °C for 10 days. The appearance of a clear (halo) zone around the colonies indicated phosphate solubilization. The phosphate solubilization index (FPI) was calculated according to Premono et al. (1996) using the following formula:

$$FPI = \frac{\text{Halo zone diameter (mm)}}{\text{Colony diameter (mm)}} \quad (1)$$

The strains were categorized as strong (FPI > 1.5), moderate (1.0 < FPI ≤ 1.5), or weak (FPI ≤ 1.0) solubilizers.

### Quantitative assessment and pH dynamics

Quantitative evaluation was performed in liquid PSB medium. 1 ml of bacterial suspension was inoculated into 50 ml Erlenmeyer flasks containing PSB and incubated at 28–30 °C for 10 days. The pH of the medium was recorded daily to monitor the production of organic acids. A significant drop in pH (from 7.0 to 5.0 or lower) indicated active phosphate solubilization.

### Molybdenum blue colorimetric assay

The concentration of dissolved orthophosphates was determined using a modified Molybdenum Blue method (He et al., 2005; Zafarjonovna et al., 2026). Bacterial cultures were centrifuged at 5000 rpm for 10 minutes. 1 ml of the supernatant was mixed with 0.5 ml of ammonium molybdate reagent, 0.5 ml of sulfuric acid, and 0.2 ml of ascorbic acid. After 10–15 minutes of incubation at room temperature, the development of a blue color intensity was analyzed, indicating the amount of solubilized phosphate.

### Growth promotion assay using wheat

To evaluate the symbiotic efficiency of the most potent strains (*P. putida* KoPr129 and *B. amyloliquefaciens* HAPH2), a pot experiment was conducted using wheat (*Triticum aestivum* L.). Seeds were surface-sterilized with 70% ethanol for 1 min and 2% sodium hypochlorite for 5 min, followed by multiple rinses with sterile distilled water. The seeds were then bacterized by immersion in a microbial suspension ($10^8$ CFU/mL) for 2 hours.

The experiment was designed with three treatments in triplicate:
- Control – non-inoculated plants under salinity stress (150 mM NaCl) and P-deficiency (insoluble $Ca_3(PO_4)_2$ as the sole P source).
- KoPr129 – wheat inoculated with *P. putida* KoPr129 under the same stress conditions.
- HAPH2 – wheat inoculated with *B. amyloliquefaciens* HAPH2 under the same stress conditions.

Plants were grown in a greenhouse for 5 weeks. At the end of the period, shoot length, root length, and total dry biomass were recorded. Total phosphorus (P) accumulation in the shoot tissues was quantified using the vanadate-molybdate colorimetric method.

### Statistical analysis

All experiments were performed in three replicates (n=3). The obtained results were presented as the mean value and standard deviation (mean ± SD). The statistical significance of the data was analyzed at a level of P≤0.01 using Origin Pro 2024 (Ergasheva et al., 2024; Rayimova et al., 2024).

## RESULTS

### Qualitative screening of phosphate solubilization

The qualitative assessment of phosphate solubilization on Pikovskaya's Agar (PVK) medium revealed that the endophytic bacterial isolates possess varying degrees of efficiency in dissolving tricalcium phosphate ($Ca_3(PO_4)_2$). The results, expressed as the FPI, indicate that the process is highly influenced by both incubation time and salinity levels (Table 2).

Throughout the 10-day experiment, *P. putida* KoPr 129 and *B. amyloliquefaciens* HAPH2 emerged as the most potent phosphate solubilizers. At 2% NaCl on Day 10, *P. putida* KoPr 129 achieved a maximum FPI of 33.96 ± 1.31 mm, followed closely by *B. amyloliquefaciens* HAPH2 with 31.28 ± 2.80 mm. There was a clear progressive increase in the diameter of the halo zones from Day 2 to Day 10 for all strains. This suggests that the bacteria continuously secrete organic acids into the surrounding medium, steadily expanding the zone of phosphate mineral dissolution. A significant inverse relationship was observed between salt concentration and solubilization efficiency. As NaCl levels increased from 2% to 10%, the FPI values decreased across all isolates. For example, the FPI of *P. putida* KoPr 129 dropped from 33.96 mm (2% NaCl) to 18.16 mm (10% NaCl). Despite the reduction in activity at higher salinity, the isolates KoPr 129 and HAPH2 maintained substantial solubilizing capacity even at 10% NaCl. This resilience distinguishes them from other strains like *B. amyloliquefaciens* KoPr101 and *P. chlororaphis* HAST17, which failed to produce halo zones under osmotic stress. Other isolates such as *B. pumilus* KoPr113, *P. aryabhattai* KoPr118, and *B. subtilis* CrEw1018 showed moderate and relatively similar FPI values (ranging from ~20 mm to 22 mm at 2% NaCl on Day 10), indicating a consistent but less aggressive phosphate-solubilizing mechanism compared to the leading strains.

The robust performance of *P. putida* KoPr129 and *B. amyloliquefaciens* HAPH2 under hypersaline conditions underscores their potential as effective bio-inoculants for enhancing phosphorus availability in saline and arid agricultural soils.

**Table 2.** Phosphate solubilization index (FPI) of endophytic bacterial strains under different NaCl concentrations over a 10-day period

| Bacterial strains | 2% NaCl (mm) | 5% NaCl (mm) | 10% NaCl (mm) |
|---|---|---|---|
| Day 2 of the experiment | | | |
| *B. pumilus* KoPr113 | 10.22±0.14 | 8.24±0.35 | 5.70±0.39 |
| *P. aryabhattai* KoPr118 | 10.34±0.31 | 8.74±0.36 | 5.48±0.30 |
| *P. putida* KoPr 129 | 12.16±0.31 | 10.20±0.47 | 9.18±0.28 |
| *B. subtilis* CrEw1018 | 9.14±0.24 | 9.26±0.17 | 7.20±0.35 |
| *B. amyloliquefaciens* HAPH2 | 11.28±0.34 | 9.66±0.41 | 8.14±0.40 |
| Day 5 of the experiment | | | |
| *B. pumilu*s KoPr113 | 18.56±0.43 | 16.50±0.50 | 12.06±0.63 |
| *P. aryabhattai* KoPr118 | 19.02±0.42 | 17.22±0.51 | 12.10±0.50 |
| *P. putida* KoPr 129 | 27.16±0.44 | 25.88±0.52 | 15.06±0.52 |
| *B. subtilis* CrEw1018 | 16.48±0.50 | 15.58±0.47 | 11.78±0.61 |
| *B. amyloliquefaciens* HAPH2 | 25.12±0.55 | 23.78±0.49 | 14.06±0.47 |
| Day 10 of the experiment | | | |
| *B. pumilus* KoPr113 | 21.88±0.47 | 19.86±0.51 | 13.34±0.53 |
| *P. aryabhattai* KoPr118 | 22.14±0.50 | 20.86±0.49 | 13.88±0.53 |
| *P. putida* KoPr 129 | 33.96±1.31 | 30.68±0.36 | 18.16±0.56 |
| *B. subtilis* CrEw1018 | 20.56±0.47 | 18.60±0.51 | 12.84±0.50 |
| *B. amyloliquefaciens* HAPH2 | 31.28±2.80 | 28.50±0.47 | 16.70±0.54 |

**Note:** Values represent the mean of three replicates ± standard deviation (SD) (n=3; P≤0.01). Figures in bold indicate the highest performance within the specific salt concentration.

### Quantitative P-solubilization and pH dynamics

The experimental data illustrated in Figure 1 confirms that the solubilization of inorganic phosphorus by the selected bacterial strains is directly linked to the acidification of the culture medium. This process is driven by the production of organic acids, a key metabolic trait for effective phosphate-solubilizing bacteria (PSB). All strains demonstrated a progressive decrease in pH from Day 2 to Day 10. This steady decline indicates continuous metabolic activity and sustained acid production throughout the incubation period. Among the tested isolates, P. putida KoPr 129 emerged as the most efficient acid producer. By Day 10, it achieved the lowest pH values across all salinity levels, reaching a minimum of 5.14 ± 0.073 at 2% NaCl. This correlates perfectly

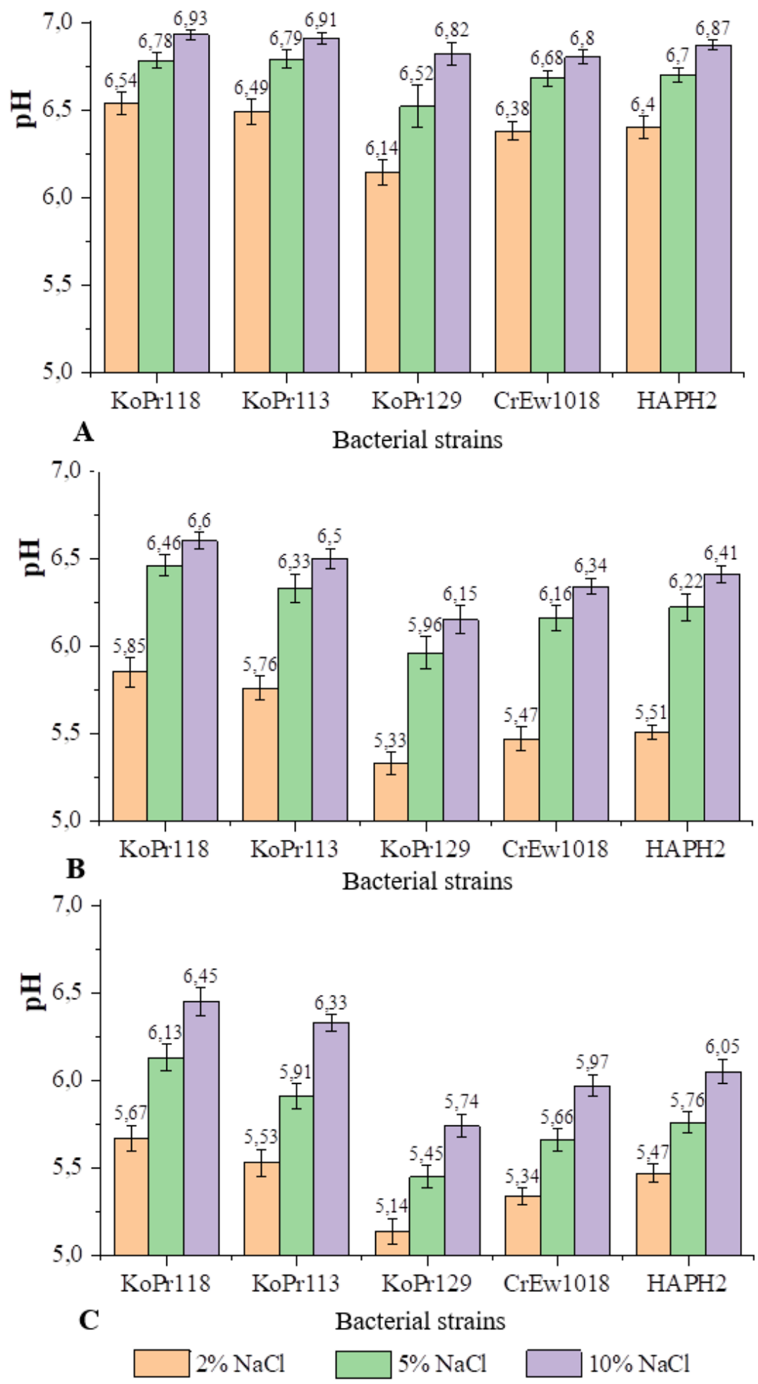


**Figure 1.** Effect of salinity on pH dynamics during phosphate solubilization by bacterial strains (A – Day 2; B – Day 5; C – Day 10; n=3; P≤0.01)

with the high intensity of phosphate solubilization observed in the previous colorimetric assays. While increasing NaCl concentrations (from 2% to 10%) generally led to higher pH values (indicating a slight inhibition of acid production), the strains remained remarkably robust. Even at 10% NaCl, *P. putida* KoPr 129 and *B. amyloliquefaciens* HAPH2 successfully lowered the pH to 5.74 and 6.05 respectively.

Other strains like KoPr 113 and KoPr 118 also showed significant acidification, though their final pH levels remained higher than those of the KoPr 129 strain, suggesting a lower rate of organic acid secretion (Figure 1).

The strong correlation between the decrease in pH and the release of dissolved orthophosphates confirms that acidogenesis is the primary mechanism for P-solubilization in these isolates. The ability of these strains to maintain acid production under hypersaline conditions (up to 10% NaCl) highlights their potential for application in salt-affected agricultural soils.

## Molybdenum blue assay and comparative efficiency

The results of the study demonstrated that all investigated bacterial isolates possess the ability to solubilize inorganic phosphates. The colorimetric assay conducted using the Molybdenum Blue method revealed a direct correlation between the intensity of the color and the concentration of dissolved orthophosphates in the medium (Figure 2).

Among the tested strains, *P. putida* KoPr 129 (Tube 5) exhibited the most potent phosphate solubilization capacity. The intensity of the blue/purple color in this isolate was significantly higher than in all other samples, indicating a superior metabolic potential for mobilizing inorganic phosphorus. The strains *B. amyloliquefaciens* HAPH2 (Tube 4) and *P. aryabhattai* KoPr 118 (Tube 3) followed in efficiency. Their color profiles differed substantially from the control, showing high effectiveness in converting insoluble phosphates into bioavailable forms. While *B. pumilus* KoPr 113 (Tube 2) and *B. subtilis* CrEw 1018 (Tube 1) also demonstrated phosphate-solubilizing traits, their activity levels were relatively lower, as evidenced by the lighter color intensity compared to the *P. putida* strain. The control variant using *E. coli* showed no color change (remaining yellow), confirming the absence of a phosphate-solubilizing mechanism in this bacterium.

## Impact of inoculation on wheat growth and P-uptake

The greenhouse experiments demonstrated that combined salinity and phosphorus-deficient stress severely inhibited the growth of wheat (*Triticum aestivum* L.). In the non-inoculated stress control group, plants exhibited stunted growth, with a significant reduction in both shoot and root development (Table 3).

However, the application of halotolerant endophytic strains significantly alleviated these negative effects. Inoculation with *P. putida* KoPr129 resulted in a 69% increase in shoot length (31.2 ± 1.8 cm) compared to the stressed control (18.4 ± 1.2 cm). *B. amyloliquefaciens* HAPH2 also showed a substantial increase of 62%. The total dry biomass of plants treated with KoPr129 was 1.62 g/plant, which is nearly double the biomass of the stressed control (0.85 g/plant).

The most critical finding was the impact on P-accumulation. While the stressed control plants

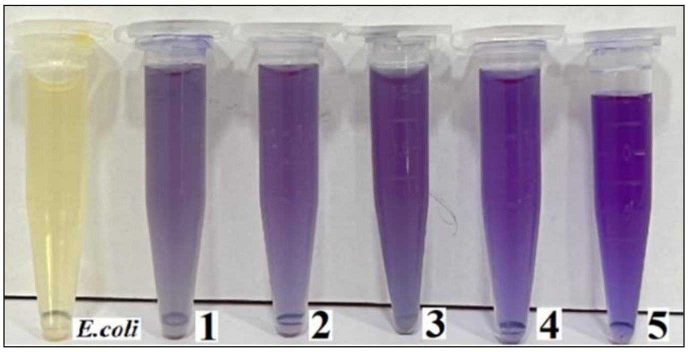


**Figure 2.** Colorimetric assay for phosphate mineralization by various bacterial isolates (Control – *E. coli*; 1 – *B. subtilis* CrEw 1018, 2 – *B. pumilus* KoPr 113, 3 – *P. aryabhattai* KoPr 118, 4 – *B. amyloliquefaciens* HAPH2, 5 – *P. putida* KoPr 129)

**Table 3.** Impact of halotolerant endophytes on wheat growth and P-uptake under 150 mM NaCl stress (n=5)

| Treatment | Shoot length (cm) | Root length (cm) | Dry biomass (g/plant) | P-uptake (mg/g dry weight) |
|---|---|---|---|---|
| Control (Stress) | 18.4 ± 1.2 | 7.6 ± 0.5 | 0.85 ± 0.08 | 0.92 ± 0.04 |
| Stress + *P. putida* KoPr129 | 31.2 ± 1.8* | 13.4 ± 0.9* | 1.62 ± 0.12* | 2.15 ± 0.11* |
| Stress + *B. amyloliquefaciens* HAPH2 | 29.8 ± 1.5* | 12.1 ± 0.7* | 1.48 ± 0.10* | 1.98 ± 0.09* |

**Note:** * $P < 0.05$.

only accumulated 0.92 mg/g of phosphorus, the KoPr129-treated plants reached 2.15 mg/g. This indicates that the bacteria successfully converted the insoluble $Ca_3(PO_4)_2$ in the soil into a bioavailable form, doubling the uptake efficiency under 150 mM NaCl stress.

## DISCUSSION

The results of this study underscore the critical role of halotolerant endophytic bacteria in mitigating the synergistic stress of salinity and phosphorus (P) deficiency, which are primary constraints in modern sustainable agriculture. As highlighted by Gilbert et al. (2010), the global increase in population necessitates innovative strategies to “feed a hungry world” without further degrading the environment. In saline-affected ecosystems, such as those found in the arid regions of Uzbekistan, P-availability is severely limited due to chemical fixation with calcium and magnesium ions. While traditional farming relies on excessive chemical P-fertilizers, Alori et al. (2017) and Jiang et al. (2018) emphasize that 60–70% of these inputs become immobilized and ecologically harmful, contributing to soil compaction and groundwater pollution.

Our findings demonstrate that the selected endophytic strains, particularly *Pseudomonas putida* KoPr 129 and *Bacillus amyloliquefaciens* HAPH2, offer a biologically viable alternative. The significant drop in pH observed in our experiments (from 7.0 down to 5.14 for KoPr 129) aligns with the mechanisms described by Hayat et al. (2010), where bacterial production of organic acids and proton exchange lower the rhizosphere pH to release soluble orthophosphates. This acidification is a key ecological “engineering” process that transforms unavailable mineral P into a bioavailable form, directly supporting plant growth under stress.

The ecological superiority of our strains lies in their remarkable halotolerance. While many PSB lose efficiency at salt concentrations above 2% NaCl, our isolates maintained high Solubilization Indices even at 10% NaCl. This is consistent with the research of Zhu et al. (2011) and Alikulov et al. (2023), who noted that halotolerant microbes from desert regions possess unique metabolic pathways to combat osmotic stress. Furthermore, being endophytic in nature—as discussed by Axanbayev et al. (2022) and Akramov et al. (2023)—these bacteria provide a more stable symbiotic relationship than rhizospheric bacteria, as they are protected from the harsh fluctuations of the external saline environment within the plant tissues.

The observed growth promotion in wheat is not merely a result of nutrient supply but a complex interaction between the endophytes and the host plant under osmotic stress. The 69% increase in shoot length and 133% increase in P-uptake by *P. putida* KoPr129 confirms that this strain maintains its metabolic machinery even at high salinity. According to Hayat et al. (2010) and Alikulov et al. (2022), many phosphate-solubilizing bacteria (PSB) fail in saline soils because high $Na^+$ concentrations inhibit their organic acid production. However, our strains (KoPr129 and HAPH2) showed a persistent drop in pH in vitro, which translated into actual P-uptake in planta. This suggests that these endophytes produce specific organic acids (such as gluconic or citric acid) that effectively chelate $Ca^{2+}$ ions from insoluble phosphorus complexes even in the presence of competing $Cl^-$ ions. Furthermore, being endophytic gives these strains a competitive advantage. As noted by Axanbayev et al. (2022), endophytes reside within the plant tissues, providing them with a buffered environment that protects them from the direct toxicity of hypersaline soil. This internal “bio-factory” ensures a steady supply of solubilized phosphorus directly to the plant’s vascular system, bypassing the soil-fixation stage where phosphorus is typically immobilized in saline-alkali soils.

From an ecological engineering perspective, the application of *P. putida* KoPr 129 as a bio-inoculant could significantly reduce the "chemical footprint" of agriculture in saline regions. By enhancing P-uptake and potentially suppressing fungal pathogens (Norboyev et al., 2024), these microbes promote a more resilient soil-plant-microbe ecosystem. In conclusion, the integration of these halotolerant endophytes into soil management practices represents a strategic move towards the bioremediation of saline lands and the realization of sustainable, eco-friendly food production systems.

## CONCLUSIONS

This study underscores the exceptional potential of halotolerant endophytic bacteria in mitigating the synergistic stress of salinity and phosphorus deficiency. The strains *Pseudomonas putida* KoPr129 and *Bacillus amyloliquefaciens* HAPH2 demonstrated remarkable metabolic resilience, maintaining active phosphate solubilization even under extreme (10% NaCl) osmotic stress. The integration of biochemical profiling and *in vivo* plant assays provided conclusive evidence that these endophytes promote wheat growth through multiple mechanisms: Effectively transforming insoluble tricalcium phosphate into bioavailable forms, resulting in a 133% increase in P-uptake; high production of IAA which significantly enhanced root and shoot development (69% increase in shoot length); acting as a biological "internal factory," providing a buffered environment against salt toxicity. Overall, the use of *P. putida* KoPr129 as a bio-inoculant represents a strategic, eco-friendly approach to «ecological engineering» in arid agricultural systems. These findings offer a viable solution for the bioremediation of saline lands in Uzbekistan, potentially reducing the chemical footprint of modern farming while ensuring sustainable food production in salt-affected regions.

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