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# PHOSPHORUS FRACTION DYNAMICS IN SOIL AS AFFECTED BY PHOSPHORUS-SOLUBILIZING BACTERIA AND INTEGRATED PHOSPHORUS FERTILIZATION

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**Abstract**

Phosphorus (P) availability in agricultural soils is limited by fixation into mineral and organic pools, reducing fertilizer use efficiency. This study evaluated the capacity of a phosphorus-solubilizing bacterial inoculant (Pseudomonas striata) combined with integrated organic–inorganic P sources to modify soil P fraction dynamics under controlled incubation. Soil (0–20 cm) was incubated in 2-kg units amended with seven treatments (T1 = control; T2 = rock phosphate; T3 = SSP; T4 = compost + RP; T5 = compost + SSP; T6 = bagasse ash + RP; T7 = bagasse ash + SSP) with and without PSB. PSB inoculation and treatment composition significantly affected all measured P fractions and their temporal trends. At early sampling (10 d), integrated SSP + bagasse ash (T7) and SSP + compost (T5) produced the largest increases in labile and moderately labile pools: e.g., ABDTPA-P (T7 = 5.70 vs control 2.74 mg $g^{-1}$) and Olsen-P (T5 = 8.04 vs control 4.28 mg $g^{-1}$). Resin-P and ethanol-extractable P followed similar patterns (resin-P T7 = 7.00 vs control 2.49 mg $g^{-1}$; ethanol extractable P T7 = 0.836 vs control 0.174 mg $L^{-1}$). Although all P pools declined with incubation time due to sorption and biological uptake, treatments T5, T7 and (in later intervals) T6 retained relatively higher P concentrations at 40–60 d. Across intervals, PSB-inoculated soils consistently showed greater P availability than non-inoculated controls (e.g., mean ABDTPA-P increase ≈ 6–8%), indicating persistent microbial enhancement of P solubilization and labile pool maintenance. The results demonstrate that PSB coupled with SSP blended with compost or bagasse ash significantly increases short-term P availability and prolongs residence of labile P in alkaline soils. Our findings support integrated biological–organic strategies to improve phosphorus use efficiency and provide a mechanistic basis for field evaluation and optimization of PSB-based P management in cropping systems.

**Keywords:** *Bioavailable phosphorus, labile soil P, phosphorus dynamics, phosphorus use efficiency, soil incubation, sustainable crop production.*

**Introduction**

Phosphorus (P) is an essential macronutrient required for plant growth and development due to its fundamental role in energy transfer, nucleic acid synthesis, and metabolic regulation. Although most agricultural soils contain substantial amounts of total phosphorus, only a very small proportion exists in plant-available forms, typically as orthophosphate ions. The majority of soil P occurs in insoluble mineral complexes or organically bound forms that are not directly accessible to plants (Richardson et al., 2011). Phosphorus deficiency remains one of the most widespread nutritional constraints to crop productivity worldwide. In calcareous and alkaline soils, applied phosphorus is rapidly converted into poorly soluble calcium phosphates, whereas in acidic soils it is fixed by iron and aluminium oxides. These fixations processes greatly reduce fertilizer phosphorus use efficiency, often to less than 20%, necessitating repeated and excessive fertilizer inputs (Shen et al., 2011; Vance et al., 2023). Such inefficiencies increase production costs, contribute eutrophication of surface waters and depletion of non-renewable phosphate rock reserves (Alewell et al., 2020). Therefore, improving soil P availability through biological and ecological approaches has become a priority for sustainable nutrient management.

Phosphorus-solubilizing bacteria (PSB) represent a key functional group of soil microorganisms that enhance phosphorus (P) bioavailability by solubilizing inorganic phosphates through the secretion of low-molecular-weight organic acids, proton extrusion, and chelation of $Ca^{2+}$, $Fe^{3+}$, and $Al^{3+}$, and by mineralizing organic P via extracellular phosphatases and phytases (Richardson et al., 2011). Their efficiency is strongly modulated by the nature of P inputs, as soluble sources such as single superphosphate (SSP) are susceptible to fixation, whereas sparingly soluble sources like rock phosphate (RP) require biological solubilization to become plant-available, and organic amendments (e.g., compost and sugarcane bagasse ash) stimulate microbial activity and reduce P fixation by improving soil physicochemical properties and complexing metal cations (Iqbal et al., 2020; Azeem et al., 2022). Synergistic effects of PSB with organic and mineral P sources have been reported to significantly increase extractable P and nutrient use efficiency (Alori et al., 2017; Zhang et al., 2023). Soil P occurs in multiple dynamic pools differing in lability and bioavailability, and incubation studies enable quantification of temporal shifts among these fractions, providing mechanistic insights into P transformation and sustainability of applied P (Negassa & Leinweber, 2023).

Although numerous studies have documented the beneficial effects of phosphorus-solubilizing bacteria and organic amendments on total or available phosphorus, most investigations have focused on single extractable P indices or short-term plant responses. Limited information is available on how **PSB interact with combined organic and inorganic phosphorus sources to regulate the temporal dynamics of multiple soil phosphorus fractions under controlled incubation conditions**. In particular, comparative evidence on the behavior of labile, moderately labile, and weakly adsorbed phosphorus pools in response to integrated nutrient management remains scarce. Therefore, the present study was conducted to evaluate the effect of PSB on different soil phosphorus fractions, assess the interactive influence of organic and inorganic phosphorus sources on P availability, and determine the temporal changes in these phosphorus pools. The findings of this experiment are expected to provide mechanistic insights into phosphorus transformation processes and to support the development of strategies for improving phosphorus use efficiency in sustainable cropping systems.

## Research methodology

A laboratory incubation study was conducted at University of Agriculture Peshawar to evaluate the effects of phosphorus (P) sources and phosphorus-solubilizing bacteria (PSB) on soil P dynamics. Surface soil (0–20 cm) was air-dried, ground, and passed through a 2-mm sieve. Two kilograms of soil were placed in plastic incubation containers and amended with the respective treatments according to the experimental design. The treatments consisted of different organic and inorganic P sources with and without PSB inoculation. Soil moisture was adjusted to field capacity (approximately 25% on a weight basis) and maintained throughout the incubation period by periodic weighing and addition of distilled water. The samples were incubated at room temperature under aerobic conditions. Soil subsamples were collected at 0, 10, 20, 40, and 60 days after incubation for determination of different phosphorus fractions. At each sampling interval, soil was analyzed for multiple P forms, including resin-extractable P, water-soluble P (paste extract), ethanol-extractable solution P, AB-DTPA extractable P, and Olsen P.

### Determination of Phosphorus Fractions

### AB-DTPA Extractable P

Soil P was extracted using the AB-DTPA method described by Soltanpour (1977). Ten grams of soil were shaken with 30 mL of AB-DTPA solution for 15 minutes and filtered through Whatman No. 42 filter paper. An aliquot of the filtrate was reacted with ascorbic acid reagent, and P concentration was determined spectrophotometrically using standard solutions (0–10 mg $L^{-1}$).

### Olsen P

Olsen P was extracted using 0.5 M sodium bicarbonate (pH 8.5). Phosphorus concentration was measured calorimetrically by the molybdenum blue method after reduction with chlorostannous chloride.

**Water-Soluble P (Paste Extract)**

Water-soluble P was determined by preparing a soil paste using distilled water. The extract was obtained through vacuum filtration and analyzed for P concentration using the ammonium molybdate blue colour method at 880 nm (Kyo et al., 1996).

**Ethanol-Extractable Solution P**

Soil at field capacity was mixed with ethanol to form a paste and filtered under vacuum. The extracted solution was analyzed for P using the molybdate blue method to estimate readily soluble P.

**Resin-Extractable P (Bioavailable P)**

Bioavailable P was determined using ion-exchange resin techniques following standard procedures described by Huettl et al. (1979) and Logan et al. (1979) to estimate labile soil P.

Statistical Analysis

The incubation data were subjected to analysis of variance to evaluate the effects of applied treatments. Treatment means were compared using the least significant difference test at the 5% probability level.

## RESULTS AND DISCUSSION

**Soil attributes before initiation of experiments**

The initial physico-chemical properties of the soil revealed a bulk density of 1.45 g $cm^{-3}$. The extractable nutrient contents showed values of 6.94 mg $kg^{-1}$ for AB-DTPA extractable nitrogen, 287 mg $kg^{-1}$ for potassium, and 2.62 mg $kg^{-1}$ for phosphorus. The Olsen and resin phosphorus concentrations were 4.29 mg $kg^{-1}$ and 2.35 mg $kg^{-1}$, respectively. The water-soluble and ethanol-extractable phosphorus were 0.703 mg $L^{-1}$ and 0.168 mg $L^{-1}$, respectively. The soil exhibited an electrical conductivity of 0.28 dS $m^{-1}$ and a pH of 7.93.

These initial soil values suggest a moderately alkaline, non-saline environment suited for crop production. However, the alkaline pH shows the potential for phosphorus fixation in calcareous soils as reported for nearby districts (Irum et al., 2017). The bulk density aligns with regional averages as reported by Mehmood et al. (2021) and falls within acceptable limits for root growth, but higher values could impede soil aeration and root penetration as per Sabir et al. (2021). The extractable nutrient levels revealed relatively low phosphorus which, combined with alkaline pH, may limit P availability despite adequate total K and low extractable nitrogen.

**Table 1. Soil physiochemical properties before execution of study.**

| Attributes | Units | Values |
|---|---|---|
| **Bulk density** | g $cm^{-3}$ | 1.45 |
| **ABDTPA N** | mg $kg^{-1}$ | 6.94 |
| **ABDTPA K** | mg $kg^{-1}$ | 287 |
| **ABDTPA P** | mg $kg^{-1}$ | 2.62 |
| **Olsen P** | mg $kg^{-1}$ | 4.29 |
| **Resin P** | mg $kg^{-1}$ | 2.35 |
| **Water soluble P** | mg $L^{-1}$ | 0.703 |
| **Ethanol extractable P** | mg $L^{-1}$ | 0.168 |
| **Electric conductivity** | dS $m^{-1}$ | 0.28 |
| **pH** | - | 7.93 |

**ABDTPA Extractable Phosphorus (mg $g^{-1}$)**

The results in Table 2 showed that ABDTPA-extractable phosphorus in soil was significantly influenced by PSB inoculation and the combined application of organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days after application, treatments receiving organic amendments with inorganic P sources, particularly T7 and T5, recorded the highest extractable P values, whereas the control consistently exhibited the lowest levels. Although extractable P decreased progressively with incubation time across all treatments, T7, T5, and T6 maintained comparatively higher P concentrations at 40 and 60 days. Soils inoculated with PSB consistently produced greater ABDTPA-P values than non-inoculated soils at each sampling interval, confirming the significant role of microbial inoculation in improving soil P availability (Rodríguez and Fraga, 1999; Ahemad and Kibret, 2014).

The enhanced soil P availability under PSB-treated plots can be attributed to microbial solubilization of sparingly soluble phosphorus through the secretion of organic acids and phosphatase enzymes, which convert unavailable P into plant-available forms (Ahemad and Kibret, 2014). The gradual decline in extractable P over time reflects adsorption to soil colloids and biological utilization; however, the presence of organic amendments likely sustained P release by stimulating microbial activity and reducing P fixation (Bhat et al., 2020). The superior performance of combined treatments suggests a synergistic interaction between PSB and organic materials that enhances P solubilization and stabilization in soil, in agreement with earlier findings that integrated P management improves phosphorus dynamics and nutrient use efficiency (Dombinov et al., 2022; Nadia et al., 2023).

**Table 2. ABDTPA extractable phosphorus (mg $g^{-1}$) as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers.**

| Organic and inorganic P (40 kg $ha^{-1}$) | 10 days | 20 days | 40 days | 60 days |
|---|---|---|---|---|
| Control (T1) | 2.74 e | 2.69 f | 2.73 e | 2.74 e |
| Rock phosphate alone(T2) | 3.02 d | 3.00 e | 3.09 d | 3.10 d |
| SSP alone(T3) | 4.93 b | 4.16 c | 3.58 b | 3.20 d |
| Compost + Rock phosphate(T4) | 3.27 c | 3.34 d | 3.38 c | 3.38 c |
| Compost + SSP(T5) | 5.39 a | 4.58 b | 3.92 a | 3.44 c |
| Sugarcane bagasse ash + Rock phosphate(T6) | 3.35 c | 3.45 d | 3.64 b | 3.66 a |
| Sugarcane bagasse ash + SSP(T7) | 5.70 a | 4.76 a | 4.07 a | 3.61 b |
| LSD for P | 0.04 | 0.09 | 0.05 | 0.06 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 4.18 a | 3.87 a | 3.65 a | 3.44 a |
| PSB ─ | 3.93 b | 3.55 b | 3.33 b | 3.17 b |
| LSD for PSB | 0.02 | 0.05 | 0.03 | 0.03 |

**Olsen Phosphorus (mg $g^{-1}$)**

Table 3 indicates that Olsen-extractable phosphorus was significantly influenced by PSB inoculation and the combined use of organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days after application, treatments integrating organic amendments with mineral P sources, particularly T5 and T7, produced the highest Olsen P values, while the control consistently recorded the lowest. Although Olsen P declined progressively with time across all treatments, T7, T6, and T5 maintained comparatively higher P levels at 40 days, and T6 and T4 at 60 days. Inoculation with PSB resulted in consistently greater Olsen P concentrations than non-inoculated soils throughout the incubation period, demonstrating the significant contribution of microbial inoculation to soil P availability (Adnan et al., 2020; Zhang et al., 2024).

The improved Olsen P under PSB-treated soils can be attributed to microbial solubilization of sparingly soluble phosphates through the production of organic acids and phosphatase enzymes, which mobilize Ca-, Fe-, and Al-bound P into plant-available forms (Adnan et al., 2020; Zhang et al., 2024). The gradual reduction in Olsen P over time reflects the dynamic balance among solubilization, plant uptake, and re-adsorption of released P onto soil colloids (Haokip et al., 2019; de Oliveira et al., 2025). The superior performance of integrated treatments such as T5 (SSP + compost) and T7 (bagasse ash + SSP) highlights the synergistic interaction between organic matter and mineral P sources, as these amendments enhance microbial activity, improve cation exchange capacity, and reduce P fixation, thereby sustaining P availability (Iqbal et al., 2024; Nhunda et al., 2024).

**Table 3. Olsen phosphorus (mg $g^{-1}$) as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers**

| **Organic and inorganic P (40 kg $ha^{-1}$)** | **10 days** | **20 days** | **40 days** | **60 days** |
|---|---|---|---|---|
| Control (T1) | 4.28 e | 4.16 f | 4.25 e | 4.25 e |
| Rock phosphate alone(T2) | 4.64 d | 4.79 e | 4.73 d | 4.76 d |
| SSP alone(T3) | 7.59 b | 5.73 c | 5.12 c | 4.67 d |
| Compost + Rock phosphate(T4) | 4.98 c | 5.53c | 5.21 c | 5.23b |
| Compost + SSP(T5) | 8.04 a | 6.55 a | 5.46 b | 5.21 b |
| Sugarcane bagasse ash + Rock phosphate(T6) | 5.09 c | 5.21 d | 5.45 b a | 5.56 a |
| Sugarcane bagasse ash + SSP(T7) | 7.97 a | 6.45 b | 5.60 a | 4.97 c |
| LSD for P | 0.13 | 0.26 | 0.08 | 0.15 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 6.29 a | 5.71 a | 5.28 a | 5.10 a |
| PSB – | 5.88 b | 5.27 b | 4.95 b | 4.80 b |
| LSD for PSB | 0.07 | 0.14 | 0.04 | 0.08 |

**Water Soluble Phosphorus in Solution (mg $L^{-1}$)**

able 4 demonstrates that water-soluble phosphorus (WSP) in soil solution was significantly affected by PSB inoculation and the combined application of organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days after application, treatments integrating organic amendments with mineral P sources, particularly T5, T3, and T7, produced the highest WSP values, whereas the control consistently showed the lowest concentrations. Although WSP declined progressively with time across all treatments, T7, T5, and T6 maintained comparatively higher values at 40 and 60 days. Soils inoculated with PSB consistently exhibited greater WSP than non-inoculated soils at each sampling interval, confirming the positive role of microbial inoculation in increasing labile soil P (Richardson, 2011; Abbasi et al., 2015; Zhang et al., 2024).

The increase in WSP under PSB treatments can be attributed to microbial solubilization of mineral and organic phosphorus through organic acid production, proton extrusion, and phosphatase activity, which mobilize Ca-, Fe-, and Al-bound phosphates into soil solution (Richardson, 2011; Abbasi et al., 2015; Zhang et al., 2024). The gradual reduction in WSP over time reflects plant uptake, microbial immobilization, and adsorption of released P onto soil colloids; however, organic amendments help sustain higher WSP by stimulating microbial activity and complexing metal ions, thereby slowing P re-fixation (Adnan et al., 2020; Iqbal et al., 2024; Nhunda et al., 2024). These results indicate that integrating PSB with organic and mineral P sources enhances both the concentration and persistence of soluble phosphorus in soil, supporting more efficient crop P acquisition (Islam et al., 2023; de Oliveira et al., 2025).

**Table 4. Water soluble phosphorus (mg $L^{-1}$) in solution as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers**

| Organic and inorganic P (40 kg $ha^{-1}$) | 10 days | 20 days | 40 days | 60 days |
|---|---|---|---|---|
| Control | 0.74 f | 0.74 g | 0.76 g | 0.76 g |
| Rock phosphate alone | 0.85 f | 0.89 f | 0.89 f | 0.92 f |
| SSP alone | 3.44 b | 2.47 c | 1.63 c | 1.14 e |
| Compost + Rock phosphate | 1.10 e | 1.18 e | 1.28 e | 1.21 e |
| Compost + SSP | 3.49 a | 2.69 b | 1.95 b | 1.34 d |
| Sugarcane bagasse ash + Rock phosphate | 1.21 d | 1.37 d | 1.56 d | 1.60 a |
| Sugarcane bagasse ash + SSP | 2.69 c | 3.02 a | 1.97 a | 1.40 c |
| LSD for P | 0.18 | 0.11 | 0.04 | 0.03 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 2.00 a | 1.85 a | 1.50 a | 1.26 a |
| PSB ─ | 1.86 b | 1.68 b | 1.37 b | 1.14 b |
| LSD for PSB | 0.10 | 0.06 | 0.02 | 0.02 |

**Water Soluble Phosphorus in Paste (mg $L^{-1}$)**

Results in Table 5 reveal that water-soluble phosphorus (WSP) in soil paste was significantly influenced by PSB inoculation and the combined use of organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days after incubation, treatments integrating organic amendments with mineral P sources, particularly T7 and T5, recorded the highest WSP values, while the control consistently exhibited the lowest concentrations. Although WSP declined with time across all treatments, T7, T5, and T6 maintained comparatively higher values at 40 and 60 days. Soils inoculated with PSB consistently showed greater WSP than non-inoculated soils throughout the incubation period, confirming the significant contribution of microbial inoculation to increasing labile soil P (Rodríguez & Fraga, 1999; Chen et al., 2006).

The enhancement of WSP under PSB treatments is attributed to microbial solubilization of fixed phosphorus through the production of organic acids and chelation of $Ca^{2+}$, $Fe^{3+}$, and $Al^{3+}$, which mobilize P into readily exchangeable forms (Rodríguez & Fraga, 1999; Chen et al., 2006). The superior performance of integrated treatments reflects synergistic effects between PSB and organic amendments, as organic carbon stimulates microbial activity and organic ligands reduce P fixation, thereby sustaining higher soluble P levels (Khan et al., 2014). The gradual decline in WSP over time is associated with adsorption onto soil colloids, microbial immobilization, and plant uptake; however, PSB-inoculated soils retained higher WSP, highlighting the key role of microbial processes in maintaining the labile P pool and improving phosphorus use efficiency (Sharma et al., 2013; Vassilev et al., 2006).

**Table 5. Water soluble phosphorus (mg $L^{-1}$) in past as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers**

| **Organic and inorganic P (40 kg ha$^{-1}$)** | **10 days** | **20 days** | **40 days** | **60 days** |
|---|---|---|---|---|
| Control | 0.42 g | 0.44 e | 0.43 e | 0.41 e |
| Rock phosphate alone | 0.50 f | 0.52 d | 0.54 d | 0.54 d |
| SSP alone | 1.87 c | 1.41 b | 0.99 b | 0.66 c |
| Compost + Rock phosphate | 0.64 e | 0.71 c | 0.75 c | 0.72 b |
| Compost + SSP | 2.13 b | 1.61 a | 1.12 a | 0.77 a |
| Sugarcane bagasse ash + Rock phosphate | 0.74 d | 0.85 b | 0.96 bc | 0.99 a |
| Sugarcane bagasse ash + SSP | 2.29 a | 1.78 a | 1.23 a | 0.87 b |
| LSD for P | 0.02 | 0.02 | 0.02 | 0.01 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 1.28 a | 1.09 a | 0.90 a | 0.74 a |
| PSB ─ | 1.17 b | 1.00 b | 0.82 b | 0.68 b |
| LSD for PSB | 0.01 | 0.01 | 0.01 | 0.01 |

**Resin Phosphorus (mg $g^{-1}$)**

Results presented in Table 6 indicate that resin-extractable phosphorus was significantly influenced by PSB inoculation and the combined application of organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days after incubation, treatments integrating organic amendments with mineral P sources, particularly T7 and T5, recorded the highest resin P values, whereas the control consistently showed the lowest concentrations. Although resin P declined progressively with time across all treatments, T7, T5, and T3 maintained comparatively higher values at 40 days, while T6, T7, and T5 exhibited higher resin P at 60 days. Soils inoculated with PSB consistently produced greater resin-extractable P than non-inoculated soils throughout the incubation period, highlighting the positive contribution of microbial inoculation to labile soil P pools (Chen et al., 2006; Vassilev et al., 2006).

The increase in resin-extractable P under PSB treatments can be attributed to microbial solubilization and mineralization of fixed phosphorus through organic acid secretion, proton extrusion, and phosphatase activity, which mobilize unavailable P into readily exchangeable forms (Chen et al., 2006; Vassilev et al., 2006). The superior performance of integrated treatments reflects synergistic interactions between PSB and organic amendments, as organic matter supports microbial proliferation and complexes metal cations, thereby reducing phosphorus fixation and sustaining higher labile P levels (Khan et al., 2014; Nautiyal et al., 2013). The gradual decline in resin P over time is associated with adsorption onto soil colloids, microbial immobilization, and plant uptake; however, PSB-inoculated soils retained higher resin P, indicating the long-term effectiveness of microbial inoculation in enhancing phosphorus availability and improving phosphorus use efficiency in sustainable cropping systems (Aloo, 2020).

**Table 6. Resin phosphorus (mg $g^{-1}$) as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers**

| Organic and inorganic P (40 kg $ha^{-1}$) | 10 days | 20 days | 40 days | 60 days |
|---|---|---|---|---|
| Control | 2.49 f | 2.45 f | 2.41 f | 2.35 f |
| Rock phosphate alone | 2.77 e | 2.80 e | 2.92 e | 2.93 e |
| SSP alone | 6.22 b | 5.12 b | 4.14 b | 3.35 d |
| Compost + Rock phosphate | 3.29 d | 3.42 d | 3.56 d | 3.47 c |
| Compost + SSP | 6.84 a | 5.58 a | 4.46 a | 3.47 c |
| Sugarcane bagasse ash + Rock phosphate | 3.45 c | 3.82 c | 3.97 c | 4.02 a |
| Sugarcane bagasse ash + SSP | 7.00 a | 5.86 a | 4.71 a | 3.72 b |
| LSD for P | 0.1 | 0.10 | 0.06 | 0.08 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 4.8 a | 4.34 a | 3.90 a | 3.47 a |
| PSB ─ | 4.4 b | 3.95 b | 3.57 b | 3.19 b |
| LSD for PSB | 0.1 | 0.05 | 0.03 | 0.04 |

**Soil ethanol extractable phosphorus (mg $L^{-1}$)**

As presented in Table 6, ethanol-extractable phosphorus (EE-P) was affected by phosphorus-solubilizing bacteria (PSB) and different organic and inorganic phosphorus sources at all sampling intervals. At 10 and 20 days, the highest EE-P values were recorded in T7 and T5, whereas T1 consistently showed the lowest phosphorus concentration. Although EE-P declined progressively at 40 and 60 days across all treatments, PSB-inoculated soils maintained higher EE-P (0.466–0.260 mg $L^{-1}$) compared to non-inoculated soils (0.424–0.234 mg $L^{-1}$).

Ethanol-extractable phosphorus represents a readily exchangeable and weakly sorbed fraction of soil P that is sensitive to biological processes. The higher EE-P under PSB inoculation can be attributed to microbial secretion of organic acids and phosphatases that dissolve mineral phosphates and desorb P from soil surfaces (Adnan et al., 2020; Islam et al., 2023; Zhang et al., 2024). The superior performance of integrated organic and inorganic P treatments reflects synergistic effects of enhanced microbial metabolism and reduced P fixation by organic matter, which together sustained labile phosphorus availability over time (Alam et al., 2022).

**Table 7. Soil ethanol extractable phosphorus (mg $L^{-1}$) as effect by phosphorus solubilizing bacteria with organic and inorganic Phosphorus fertilizers.**

| Organic and inorganic P (40 kg $ha^{-1}$) | 10 days | 20 days | 40 days | 60 days |
|---|---|---|---|---|
| Control | 0.174 f | 0.174 g | 0.170 g | 0.162 g |
| Rock phosphate alone | 0.194 e | 0.196 f | 0.196 f | 0.199 f |
| SSP alone | 0.682 b | 0.519 c | 0.372 c | 0.257 d |
| Compost + Rock phosphate | 0.222 d | 0.236 e | 0.245 e | 0.242 e |
| Compost + SSP | 0.772 a | 0.585 b | 0.439 b | 0.288 b |
| Sugarcane bagasse ash + Rock phosphate | 0.236 c | 0.265 d | 0.294 d | 0.288 b |
| Sugarcane bagasse ash + SSP | 0.836 a | 0.623 a | 0.460 a | 0.291 a |
| LSD for P | 0.016 | 0.013 | 0.021 | 0.012 |
| **Phosphate solubilizing bacteria (PSB)** | | | | |
| PSB + | 0.466 a | 0.385 a | 0.323 a | 0.260 a |
| PSB — | 0.424 b | 0.357 b | 0.298 b | 0.234 b |
| LSD for PSB | 0.009 | 0.007 | 0.011 | 0.006 |

## Conclusion

The results of this incubation study demonstrate that PSB significantly enhanced soil phosphorus availability across all measured fractions and sampling intervals. Integrated application of organic amendments with mineral P sources, particularly SSP combined with compost or sugarcane bagasse ash, consistently produced the highest levels of labile and moderately labile P pools. Although all phosphorus fractions declined over time due to sorption and biological utilization, PSB-inoculated treatments maintained higher P concentrations than non-inoculated soils, indicating sustained solubilization and mineralization processes. These findings confirm the synergistic role of microbial inoculants and organic materials in reducing P fixation and improving P use efficiency. Therefore, integrating PSB with organic and inorganic phosphorus fertilizers represents an effective and environmentally sound strategy for optimizing soil P dynamics and supporting sustainable crop production.

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