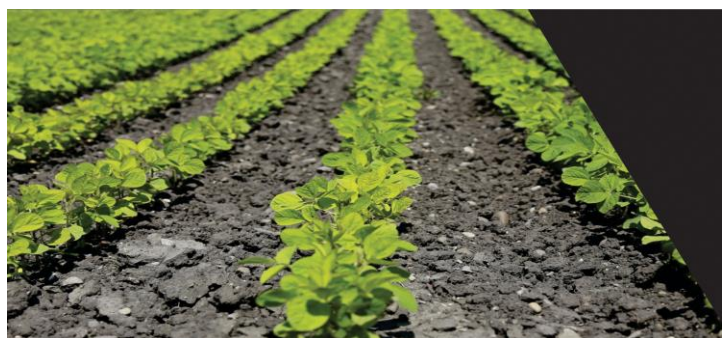




# International Journal of Research in Agronomy

E-ISSN: 2618-0618  
P-ISSN: 2618-060X  
© Agronomy  
NAAS Rating (2026): 5.20  
[www.agronomyjournals.com](http://www.agronomyjournals.com)  
2026; 9(9): 596-603  
Received: 12-07-2026  
Accepted: 17-08-2026

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## Effect of Microbial Enriched Granulated Rock Phosphate on Performance of Cluster Bean (*Cyamopsis* *tetragonoloba* L.) and Soil Phosphorus Availability

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**DOI:** <https://www.doi.org/10.33545/2618060X.2026.v9.i9h.6572>

### Abstract

A field experiment was conducted during Rabi 2025-26 at the Main Agricultural and Horticultural Research Station (MAHRS), Iruvakk, Shivamogga, Karnataka, to evaluate the effect of microbially enriched granulated rock phosphate (GRP) on growth, yield and nutrient status of cluster bean (*Cyamopsis tetragonoloba* L.) and on soil phosphorus availability in an acidic sandy clay loam soil (pH 5.80, available  $P_2O_5$  17.83 kg ha<sup>-1</sup>). The experiment, laid out in a randomized complete block design with eight treatments and three replications, compared an absolute control and recommended dose of fertilizer (RDF) against unenriched and microbially enriched granulated low-grade rock phosphate (LGRP) applied at 50, 75, 100 and 125 per cent of the recommended dose of phosphorus (RDP), the enrichment being carried out with a consortium of phosphate-solubilizing bacteria (PSB), potassium-mobilizing bacteria (KMB) and Azotobacter. Application of 75 per cent RDP through enriched GRP (T<sub>7</sub>) produced the tallest plants, the highest branching, leaf area index and biomass, and the highest pod yield (62.33 q ha<sup>-1</sup>), on par with 100 per cent RDP through enriched GRP (T<sub>6</sub>, 58.00 q ha<sup>-1</sup>), and significantly higher than RDF (41.00 q ha<sup>-1</sup>) and the absolute control (28.33 q ha<sup>-1</sup>). Enriched GRP treatments also recorded the highest N, P, K and Zn concentration and uptake, and significantly lowered soil P-fixing capacity while enriching the labile phosphorus fractions (Saloid-P, Al-P, Ca-P and organic P) at the expense of recalcitrant Fe-P, reductant-soluble P and occluded P. An accompanying incubation study confirmed that the clay-humic acid granulated carrier sustained viable populations of the three microbial groups above the recommended threshold (10<sup>7</sup> CFU g<sup>-1</sup>) for up to eight weeks. The results demonstrate that microbial enrichment of indigenous low-grade rock phosphate can substitute up to 25 per cent of the recommended chemical phosphate dose without yield penalty, offering a cost-effective and environmentally sustainable phosphorus management strategy for cluster bean in P-deficient acid soils.

**Keywords:** Cluster bean, granulated rock phosphate, phosphate-solubilizing microorganisms, phosphorus fixation, phosphorus fractions

### 1. Introduction

Phosphorus (P) ranks among the most critical yet poorly managed plant macronutrients. Although P is the eleventh most abundant element in the Earth's crust, barely 0.1 per cent of soil phosphorus is readily available to plants, and the balance is locked in sparingly soluble or fixed forms (Anandham, 2007) [3]. Nearly 67 per cent of the world's cultivated land is P-deficient (Dhillon et al., 2017) [10], and in acidic tropical and sub-tropical soils, phosphate fixation by iron and aluminium oxides such as goethite, gibbsite and kaolinite (Penn and Camberato, 2019) [24] further limits its availability, so that only 10-25 per cent of applied phosphatic fertilizer is utilised by the crop in the season of application.

Global demand for phosphatic fertilizer is met chiefly from high-grade rock phosphate (HGRP, > 13.1% P), reserves of which are finite and geographically concentrated. India's own reserves of about 200 million tonnes are overwhelmingly low-grade (LGRP, < 8.73% P), forcing the country to import roughly 7.5 million tonnes of HGRP every year (Anandham, 2007) [3]. Direct field application of LGRP is agronomically inefficient because of its poor solubility, but inoculation with phosphate-solubilizing microorganisms (PSM) bacteria such as Bacillus and

*Pseudomonas* and fungi such as *Trichoderma* and *Aspergillus* can markedly accelerate its dissolution through the production of organic acids, siderophores and phosphatase enzymes (Farrag and Bakr, 2023) <sup>[11]</sup>, offering a low-cost, sustainable route to unlock indigenous LGRP reserves.

Cluster bean (*Cyamopsis tetragonoloba* L.), known locally as 'gorikayi', is a drought-tolerant kharif legume of considerable economic importance in the dryland tracts of Karnataka, valued for its tender pods, fodder, green manure and guar-gum industrial value. Being a legume, cluster bean fixes atmospheric nitrogen symbiotically through *Rhizobium*, a process itself highly P-dependent, so adequate phosphorus nutrition is central to its nodulation, growth and pod yield (Sharif *et al.*, 2013) <sup>[27]</sup>. Despite this, biologically enriched rock phosphate has been little explored as a P source for cluster bean, and the manner in which such enrichment alters soil P fractions (saloid-, Al-, Fe-, Ca-, reductant-soluble, occluded and organic-P) and P-fixing capacity over the crop cycle remains poorly documented for the acid soils of the hilly zone of Karnataka.

Against this background, the present investigation was undertaken to evaluate the effect of microbial enriched granulated rock phosphate on (i) the growth and yield performance of cluster bean, (ii) nutrient concentration and uptake by the crop, and (iii) the status and dynamics of soil phosphorus, with a view to developing a cost-effective and environmentally sustainable phosphorus nutrition strategy for cluster bean cultivation in P-deficient acid soils.

## 2. Materials and Methods

### 2.1 Experimental site, soil and season

The field experiment was conducted during Rabi 2025-26 at the Main Agricultural and Horticultural Research Station (MAHRS), Iruvakk, Shivamogga, which falls under the Hilly Zone (Agro-Climatic Zone-9) of Karnataka (14° 0' N, 75° 42' E; 620 m MSL). The experimental soil was sandy clay loam in texture, strongly acidic (pH 5.80), with an electrical conductivity of 0.567 dS m<sup>-1</sup>, organic carbon 21.6 g kg<sup>-1</sup>, available N 175.61, available P<sub>2</sub>O<sub>5</sub> 17.83 and available K<sub>2</sub>O 321.96 kg ha<sup>-1</sup>, and an initial P-fixing capacity of 89.50 mg P fixed kg<sup>-1</sup> soil.

### 2.2 Treatments and design

The experiment was laid out in a Randomized Complete Block Design with eight treatments replicated thrice (gross plot 5 × 3.0 m; net plot 4.5 × 2.7 m). Cluster bean variety Shigra was sown at 45 × 25 cm spacing with FYM at 10 t ha<sup>-1</sup> (common to all treatments except T<sub>1</sub>) and a recommended dose of fertilizer (RDF) of 25:75:60 kg N:P<sub>2</sub>O<sub>5</sub>:K<sub>2</sub>O ha<sup>-1</sup>. The treatment details are given in Table 1.

**Table 1:** Treatment details

| Treatment      | Description                                                                           |
|----------------|---------------------------------------------------------------------------------------|
| T <sub>1</sub> | Absolute control                                                                      |
| T <sub>2</sub> | RDF (25:75:60 kg N:P <sub>2</sub> O <sub>5</sub> :K <sub>2</sub> O ha <sup>-1</sup> ) |
| T <sub>3</sub> | 125% RDP through unenriched GRP                                                       |
| T <sub>4</sub> | 100% RDP through unenriched GRP                                                       |
| T <sub>5</sub> | 125% RDP through microbially enriched GRP                                             |
| T <sub>6</sub> | 100% RDP through microbially enriched GRP                                             |
| T <sub>7</sub> | 75% RDP through microbially enriched GRP                                              |
| T <sub>8</sub> | 50% RDP through microbially enriched GRP                                              |

RDP = Recommended dose of phosphorus; GRP = Granulated rock phosphate. FYM and the recommended doses of N and K were common to all treatments except T<sub>1</sub>.

### 2.3 Preparation of microbial enriched granulated rock phosphate

Rock phosphate (total P 9.84%, water-soluble P 0.003%, citrate-soluble P 1.23%; pH 8.40) was granulated (1-5 mm) using clay and humic acid as binder, and the granules were inoculated with a consortium of phosphate-solubilizing bacteria (PSB), potassium-mobilizing bacteria (KMB) and *Azotobacter* at 100 ml kg<sup>-1</sup>. An accompanying 8-week incubation study monitored the survival of the three microbial groups on the granulated carrier; all three commenced at 10<sup>8</sup> CFU g<sup>-1</sup>, peaked in the third week (*Azotobacter* ~7×10<sup>8</sup>, PSB ~6×10<sup>8</sup> and KMB ~5×10<sup>8</sup> CFU g<sup>-1</sup>) and thereafter declined gradually, remaining above the recommended viability threshold of 10<sup>7</sup> CFU g<sup>-1</sup> up to 7-8 weeks.

### 2.4 Observations and analytical methods

Plant height, number of branches, leaf area index, fresh and dry weight were recorded at 30, 60, 90 and 120 days after sowing (DAS); yield attributes (pods plant<sup>-1</sup>, pod yield plot<sup>-1</sup> and ha<sup>-1</sup>) were recorded at harvest. Nitrogen, phosphorus, potassium and zinc concentration and uptake in plant tissue were estimated at all four growth stages following standard procedures. Soil samples drawn at 30, 60, 90 and 120 DAS were analysed for pH and EC (Jackson, 1973) <sup>[17]</sup>, organic carbon (Walkley and Black, 1934) <sup>[34]</sup>, available N (Subbaiah and Asija, 1956) <sup>[31]</sup>, available P (Bray and Kurtz, 1945) <sup>[7]</sup>, available K (flame photometry), exchangeable Ca and Mg (versenate titration), available S (turbidimetry), DTPA-extractable micronutrients (Lindsay and Norvell, 1978) <sup>[21]</sup>, P-fixing capacity (equilibration with 200 ppm P followed by Bray extraction) and inorganic P fractionation (modified Chang and Jackson procedure) into saloid-P, Al-P, Fe-P, Ca-P, reductant-soluble P, occluded P, organic P and total P.

### 2.5 Statistical analysis

Data were analysed by analysis of variance as described by Gomez and Gomez (1984) <sup>[13]</sup>, and treatment means were compared using critical difference (CD) at P = 0.05.

## 3. Results and Discussion

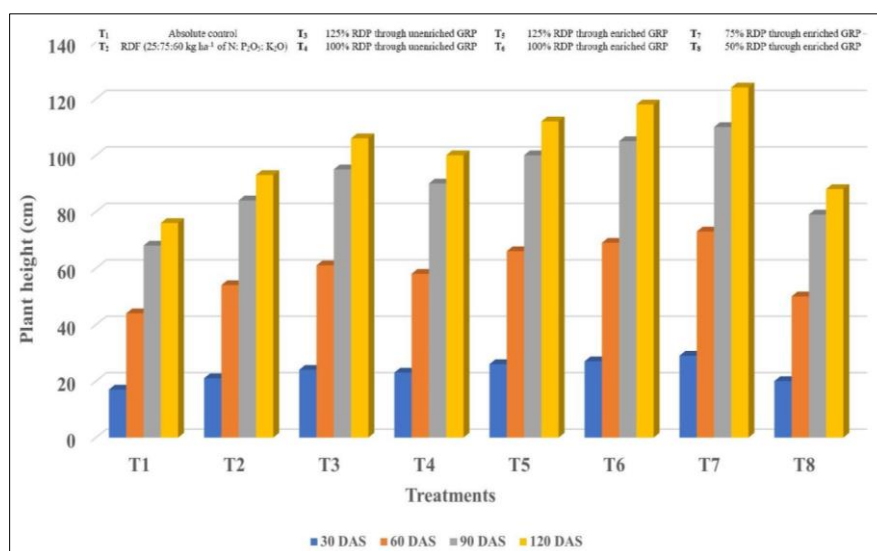
### 3.1 Growth parameters

Plant height, branching, leaf area index (LAI) and biomass accumulation were significantly influenced by microbial enrichment of GRP at every stage of crop growth (Table 2, Fig. 1). Treatment T<sub>7</sub> (75% RDP through enriched GRP) recorded the tallest plants (124 cm at 120 DAS), the highest branching (12 plant<sup>-1</sup>) and the highest LAI (4.5), and was statistically on par with T<sub>6</sub> (100% RDP through enriched GRP: 118 cm, 11 branches, LAI 4.3) at most stages, while the absolute control (T<sub>1</sub>) remained the shortest throughout (76 cm, 7 branches, LAI 2.0 at 120 DAS). The superiority of enriched GRP treatments, and in particular the fact that T<sub>7</sub> outperformed T<sub>5</sub> (125% RDP through enriched GRP) despite receiving a lower P dose, reflects sustained microbial mobilisation of P from GRP through organic-acid and phosphatase activity of the PSB-KMB-*Azotobacter* consortium, consistent with reports of enhanced plant height and biomass in cluster bean and other legumes following PSM-enriched rock phosphate or bio-processed RP application (Yadav and Tarafdar, 2011; Chauhan *et al.*, 2017; Vassilev *et al.*, 2001; Biswas and Narayanasamy, 2006) <sup>[35, 8, 33, 5]</sup>. Adequate P nutrition supports cell division, root proliferation, cytokinin-mediated lateral branching and canopy photosynthetic capacity (Grant *et al.*, 2001; Garg and Chandel, 2010) <sup>[14, 12]</sup>, explaining the parallel improvement across all growth attributes in the enriched-GRP treatments.

**Table 2:** Growth and yield attributes of cluster bean at harvest (120 DAS) as influenced by microbial enriched granulated rock phosphate

| Treatment                                | Plant height (cm) | Branches plant <sup>-1</sup> | LAI  | Pods plant <sup>-1</sup> | Pod yield (q ha <sup>-1</sup> ) |
|------------------------------------------|-------------------|------------------------------|------|--------------------------|---------------------------------|
| T <sub>1</sub> - Absolute control        | 76                | 7                            | 2.0  | 38                       | 28.33                           |
| T <sub>2</sub> - RDF                     | 93                | 8                            | 3.2  | 56                       | 41.00                           |
| T <sub>3</sub> - 125% RDP unenriched GRP | 106               | 10                           | 3.8  | 68                       | 49.33                           |
| T <sub>4</sub> - 100% RDP unenriched GRP | 100               | 9                            | 3.5  | 63                       | 46.33                           |
| T <sub>5</sub> - 125% RDP enriched GRP   | 112               | 10                           | 4.1  | 74                       | 53.66                           |
| T <sub>6</sub> - 100% RDP enriched GRP   | 118               | 11                           | 4.3  | 80                       | 58.00                           |
| T <sub>7</sub> - 75% RDP enriched GRP    | 124               | 12                           | 4.5  | 86                       | 62.33                           |
| T <sub>8</sub> - 50% RDP enriched GRP    | 88                | 8                            | 2.9  | 50                       | 38.00                           |
| S.Em±                                    | 2.88              | 0.32                         | 0.15 | 2.1                      | 1.47                            |
| CD (P=0.05)                              | 8.79              | 0.98                         | 0.46 | 6.38                     | 4.47                            |

Values shown are at 120 DAS (harvest). LAI = Leaf area index.

**Fig 1:** Effect of microbial enriched granulated rock phosphate on plant height of cluster bean at 30, 60, 90 and 120 DAS

### 3.2 Yield attributes

Pod number, pod yield plot<sup>-1</sup> and pod yield ha<sup>-1</sup> followed the same treatment order as the growth parameters (Table 2). T<sub>7</sub> produced the highest pod yield (62.33 q ha<sup>-1</sup>), statistically on par with T<sub>6</sub> (58.00 q ha<sup>-1</sup>) and significantly higher than the standard RDF (T<sub>2</sub>, 41.00 q ha<sup>-1</sup>) and the absolute control (T<sub>1</sub>, 28.33 q ha<sup>-1</sup>). Notably, T<sub>7</sub> out-yielded RDF by roughly 52 per cent while supplying only 75 per cent of the recommended P dose, underlining the extent to which microbial solubilization can substitute for chemical P input. Similar yield advantages of rock-phosphate-enriched-compost or PSB-inoculated rock phosphate over standard fertilizer doses have been reported in mung bean (Kumari *et al.*, 2024) [20], chickpea (Allah Ditta *et al.*, 2018) [1] and cluster bean (Chauhan *et al.*, 2017) [8], attributed to progressive P release synchronised with crop demand and sustained availability through the reproductive phase, reducing flower and pod drop (Khan *et al.*, 2007) [18].

### 3.3 Nutrient concentration and uptake

Nitrogen, phosphorus, potassium and zinc concentration in plant tissue, and their total uptake, were significantly higher under microbially enriched GRP at every growth stage (Table 3, Figs. 2-4). At 120 DAS, T<sub>7</sub> removed 113.29 kg N, 12.67 kg P and 54.57 kg K ha<sup>-1</sup> and 142 g Zn ha<sup>-1</sup>, values statistically on par with T<sub>6</sub> and significantly greater than RDF (T<sub>2</sub>: 93.57 kg N, 10.01 kg P, 44.85 kg K ha<sup>-1</sup>) and the control (T<sub>1</sub>: 88.32 kg N, 9.39 kg P, 42.63 kg K ha<sup>-1</sup>). Because P is a prerequisite for ATP-driven nitrogenase activity in root nodules, enhanced P supply under enriched GRP directly supported greater biological nitrogen fixation and N accumulation (Peoples *et al.*, 2009) [25], while P-induced improvements in root architecture increased K uptake via mass flow (Haq and Mallarino, 2000) [15] and organic-acid-mediated rhizosphere chelation mobilised zinc (Alloway, 2008) [2], collectively explaining the parallel gains across all four nutrients.

**Table 3:** Nutrient uptake by cluster bean at harvest (120 DAS) as influenced by microbial enriched granulated rock phosphate

| Treatment                                | N uptake (kg ha <sup>-1</sup> ) | P uptake (kg ha <sup>-1</sup> ) | K uptake (kg ha <sup>-1</sup> ) | Zn uptake (g ha <sup>-1</sup> ) |
|------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| T <sub>1</sub> - Absolute control        | 88.32                           | 9.39                            | 42.63                           | 68                              |
| T <sub>2</sub> - RDF                     | 93.57                           | 10.01                           | 44.85                           | 82                              |
| T <sub>3</sub> - 125% RDP unenriched GRP | 100.64                          | 10.91                           | 48.09                           | 105                             |
| T <sub>4</sub> - 100% RDP unenriched GRP | 98.62                           | 10.26                           | 47.39                           | 98                              |
| T <sub>5</sub> - 125% RDP enriched GRP   | 104.87                          | 11.31                           | 50.37                           | 122                             |
| T <sub>6</sub> - 100% RDP enriched GRP   | 111.44                          | 11.91                           | 54.14                           | 132                             |
| T <sub>7</sub> - 75% RDP enriched GRP    | 113.29                          | 12.67                           | 54.57                           | 142                             |
| T <sub>8</sub> - 50% RDP enriched GRP    | 90.50                           | 9.75                            | 43.80                           | 74                              |
| S.Em±                                    | 1.42                            | 0.18                            | 0.72                            | 3.25                            |
| CD (P=0.05)                              | 4.31                            | 0.55                            | 2.19                            | 9.88                            |

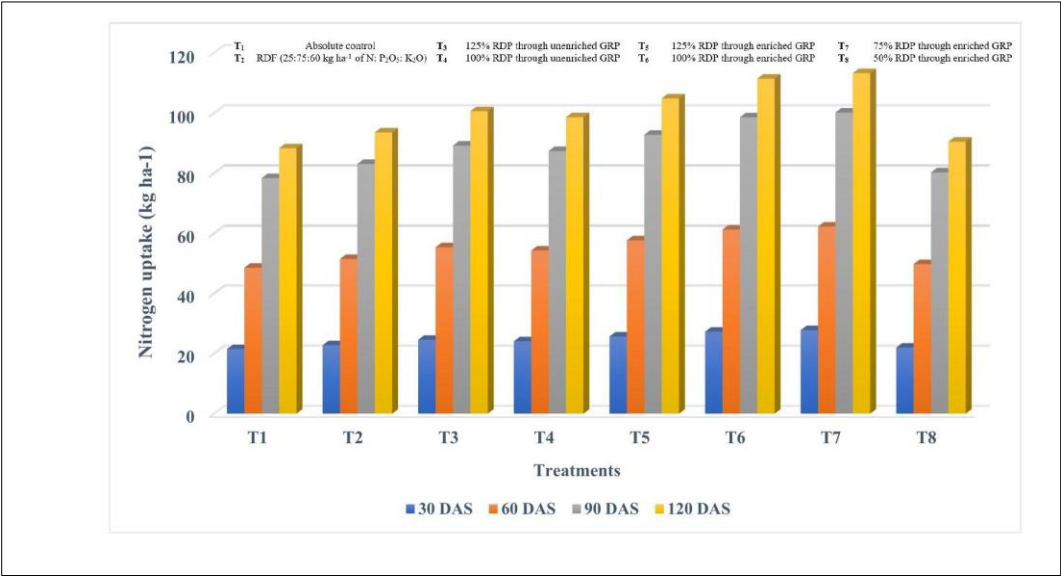


**Fig 2:** Effect of microbial enriched granulated rock phosphate on nitrogen uptake under cluster bean at 30, 60, 90 and 120 DAS

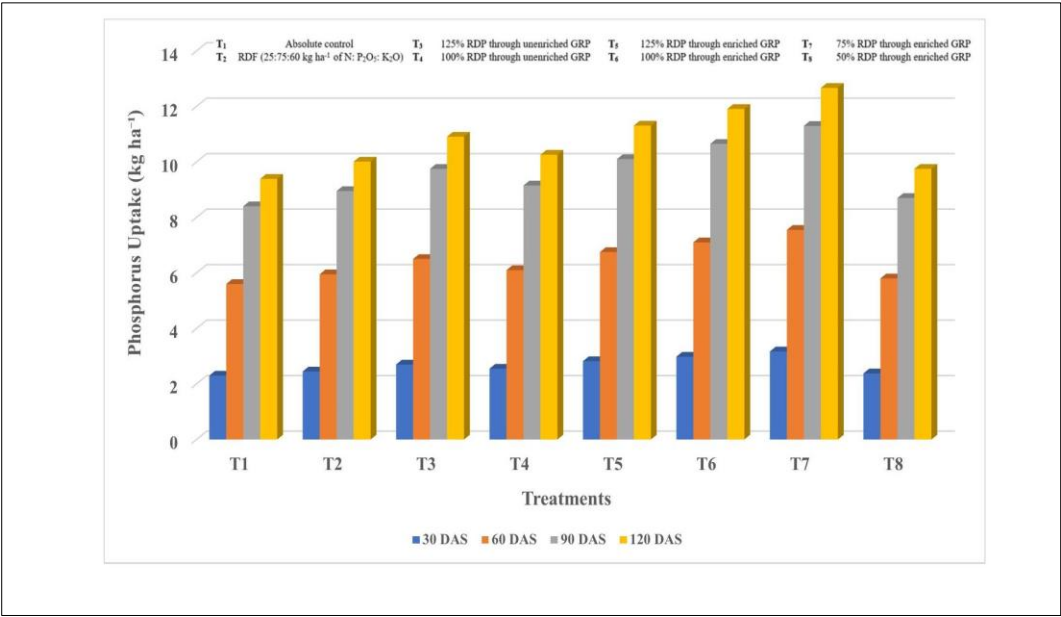


**Fig 3:** Effect of microbial enriched granulated rock phosphate on phosphorus uptake under cluster bean at 30, 60, 90 and 120 DAS

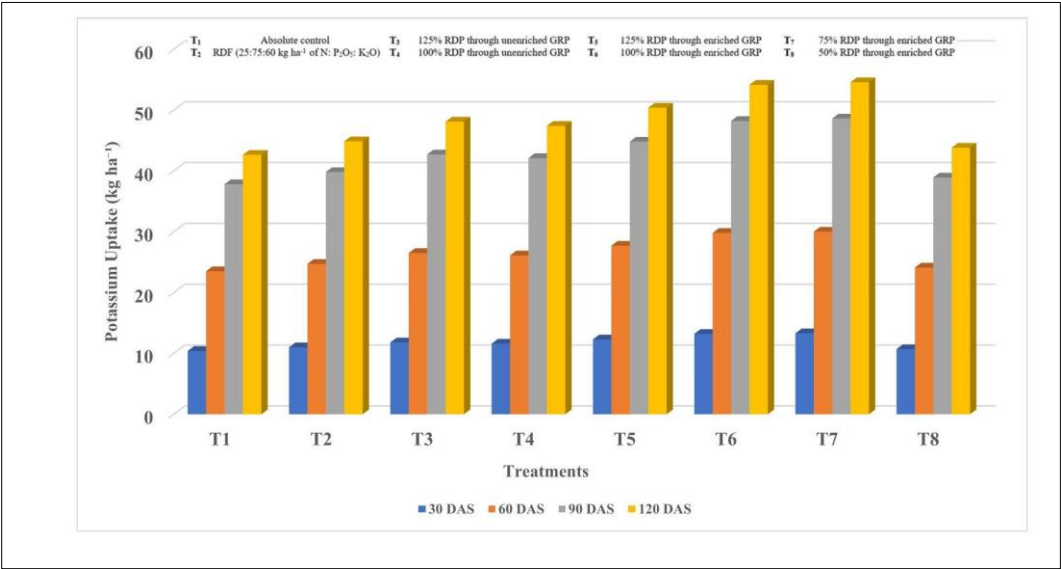


**Fig 4:** Effect of microbial enriched granulated rock phosphate on potassium uptake under cluster bean at 30, 60, 90 and 120 DAS

### 3.4 Available soil phosphorus

Soil available  $P_2O_5$  declined progressively from 30 to 120 DAS in all treatments owing to continuous crop uptake (Table 4, Fig. 5). RDF ( $T_2$ ) recorded the highest available P at every stage ( $68.65 \text{ kg ha}^{-1}$  at 120 DAS), reflecting the immediate solubility of chemical superphosphate. Among the GRP treatments, however, available P was consistently graded with the enrichment and dose:  $T_5$  (125% RDP enriched) retained the most available P among GRP treatments ( $53.48 \text{ kg ha}^{-1}$  at 120 DAS), followed by  $T_6$  and  $T_7$ , all substantially higher than their unenriched counterparts ( $T_3$ ,  $T_4$ ) and the absolute control ( $5.10 \text{ kg ha}^{-1}$ ). This confirms that microbial solubilization released P from GRP progressively through the season rather than as an immediate flush, consistent with the biphasic release pattern documented for bio-processed rock phosphate (Vassilev *et al.*, 2001; Biswas and Narayanasamy, 2006; Meena and Biswas, 2015) [33, 5, 22].

### 3.5 Soil phosphorus-fixing capacity

P-fixing capacity was consistently highest in the absolute control ( $88.6\text{--}89.8 \text{ mg P fixed kg}^{-1}$  across stages) and was significantly and progressively lowered by microbial enrichment, reaching its minimum under  $T_5$  ( $61.3 \text{ mg P fixed kg}^{-1}$  at 120 DAS), followed by  $T_6$  ( $64.9$ ) and  $T_7$  ( $68.5 \text{ mg kg}^{-1}$ ), while unenriched GRP treatments ( $T_3$ ,  $T_4$ ) remained closer to the control (Table 4, Fig. 6). This reduction is attributable to organic acids (citric, gluconic, oxalic) produced by the PSB-KMB-Azotobacter consortium, which compete with phosphate ions for sorption sites on Fe and Al oxide surfaces, thereby lowering fixation (Bolan *et al.*, 1994; Hinsinger, 2001) [6, 16], a mechanism corroborated by reports of reduced P-fixation in laterite soils following inoculation with *Aspergillus tubingensis* and *Trichoderma viride* (Pradhan and Sukla, 2006) [26].

**Table 4:** Available soil  $P_2O_5$  and soil P-fixing capacity at critical growth stages as influenced by microbial enriched granulated rock phosphate

| Treatment                       | Avail. $P_2O_5$ 30 DAS | Avail. $P_2O_5$ 120 DAS ( $\text{kg ha}^{-1}$ ) | P-fixing 30 DAS | P-fixing 120 DAS ( $\text{mg kg}^{-1}$ ) |
|---------------------------------|------------------------|-------------------------------------------------|-----------------|------------------------------------------|
| $T_1$ - Absolute control        | 16.20                  | 5.10                                            | 88.6            | 89.8                                     |
| $T_2$ - RDF                     | 85.97                  | 68.65                                           | 84.3            | 77.8                                     |
| $T_3$ - 125% RDP unenriched GRP | 54.46                  | 35.65                                           | 85.8            | 79.6                                     |
| $T_4$ - 100% RDP unenriched GRP | 48.24                  | 30.57                                           | 86.7            | 81.5                                     |
| $T_5$ - 125% RDP enriched GRP   | 72.93                  | 53.48                                           | 78.4            | 61.3                                     |
| $T_6$ - 100% RDP enriched GRP   | 62.25                  | 41.79                                           | 80.6            | 64.9                                     |
| $T_7$ - 75% RDP enriched GRP    | 51.51                  | 29.74                                           | 82.8            | 68.5                                     |
| $T_8$ - 50% RDP enriched GRP    | 43.00                  | 26.12                                           | 84.9            | 73.2                                     |
| S.Em $\pm$                      | 1.52                   | 1.02                                            | 0.62            | 1.08                                     |
| CD ( $P=0.05$ )                 | 4.61                   | 3.09                                            | 1.88            | 3.28                                     |

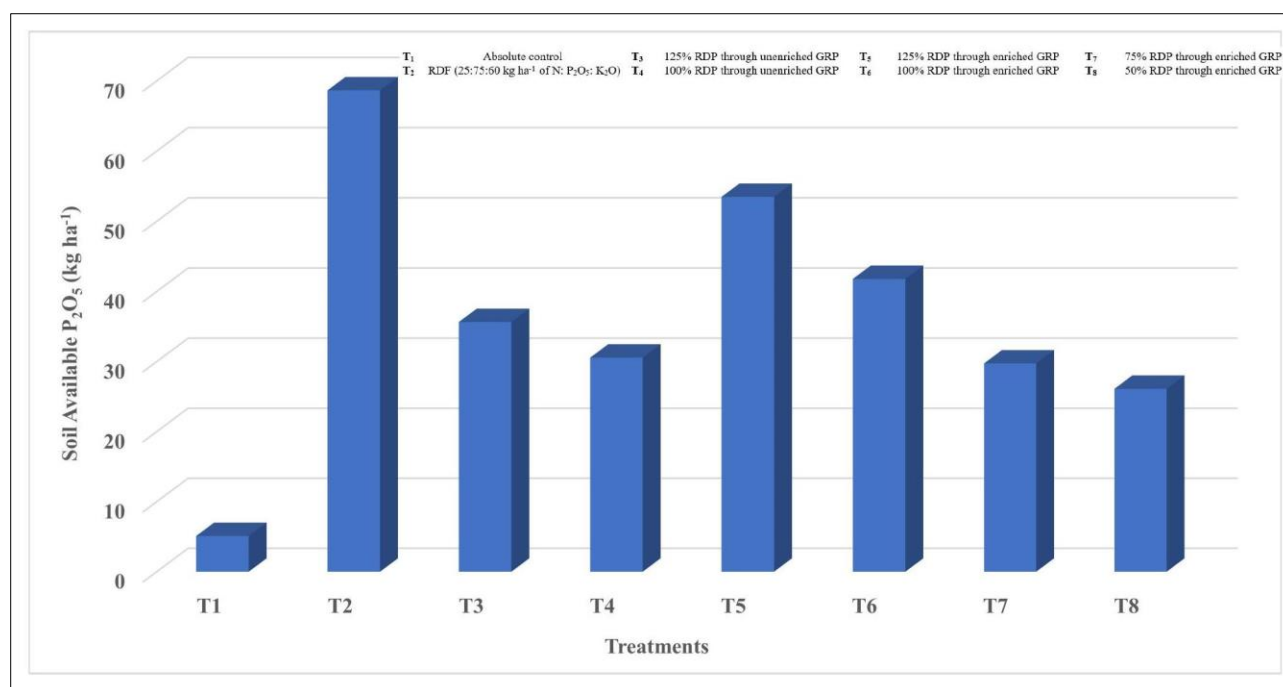


**Fig 5:** Effect of microbial enriched granulated rock phosphate on soil available  $P_2O_5$  ( $\text{kg ha}^{-1}$ ) at 120 DAS under cluster bean

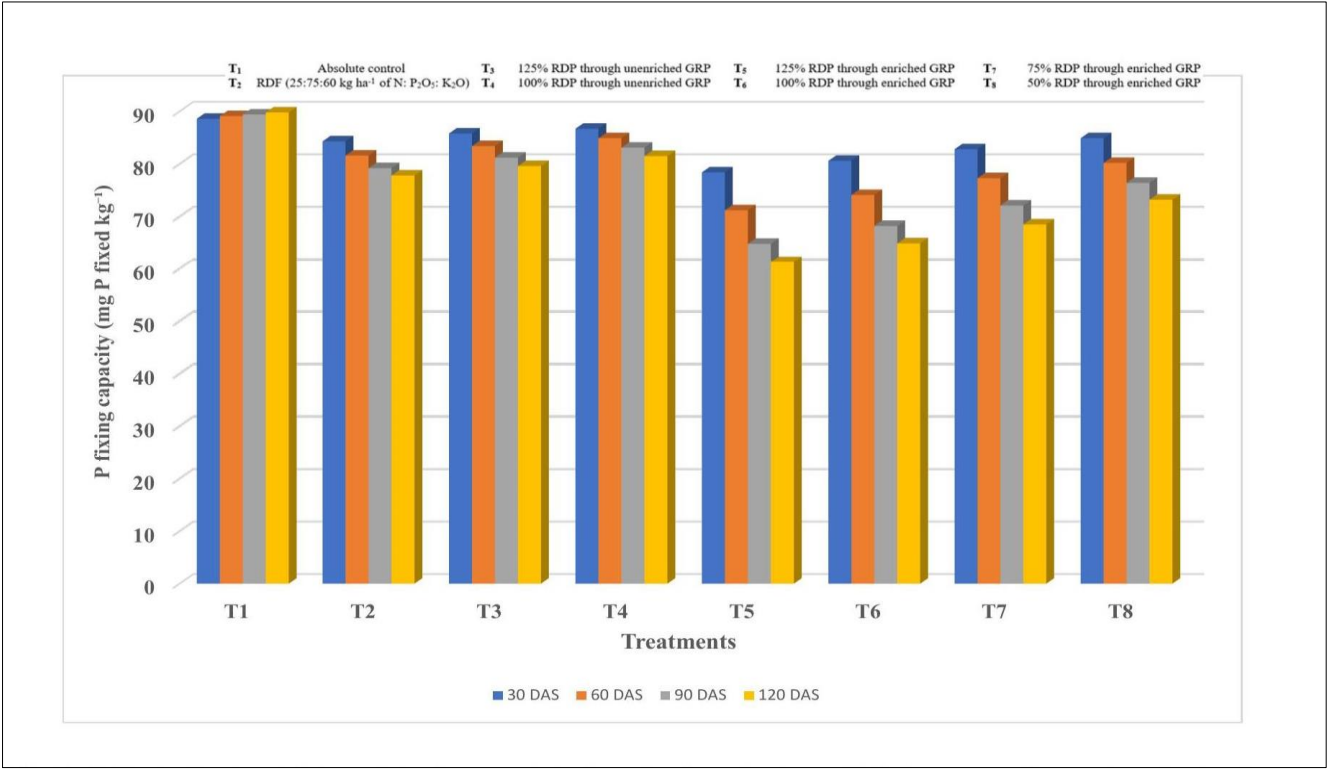


**Fig 6:** Effect of microbial enriched granulated rock phosphate on P-fixing capacity under cluster bean at 30, 60, 90 and 120 DAS

3.6 Soil inorganic phosphorus fractions

Microbial enrichment of GRP produced a clear redistribution of soil P among inorganic fractions (Table 5, Fig. 7). Labile fractions - saloid-P, Al-P, Ca-P and organic-P were consistently highest under T<sub>5</sub>, followed by T<sub>6</sub> and T<sub>7</sub>, while the recalcitrant, plant-unavailable fractions Fe-P, reductant-soluble P and occluded P were correspondingly lowest under the same treatments and highest in the absolute control. At 120 DAS, for instance, T<sub>5</sub> recorded the highest Saloid-P (5.10 mg kg<sup>-1</sup>), Al-P (122.4 mg kg<sup>-1</sup>) and Ca-P (136.4 mg kg<sup>-1</sup>) alongside the lowest Fe-P (96.6 mg kg<sup>-1</sup>), against 0.60, 40.8 and 48.2 mg kg<sup>-1</sup> (Saloid-P, Al-P, Ca-P)

and 177.4 mg kg<sup>-1</sup> Fe-P in the control. This pattern reflects organic-acid-mediated dissolution of iron-bound phosphate complexes and re-adsorption of the released phosphate onto more labile aluminium and calcium-associated forms, i.e. an active redistribution among P pools rather than a uniform response of all fractions, as similarly reported by Chen *et al.* (2006) <sup>[9]</sup>, Sharma and Kapoor (2016) <sup>[29]</sup> and Singh and Tripathi (2013) <sup>[30]</sup>. Total soil P was likewise better conserved under enriched GRP (521 mg kg<sup>-1</sup> in T<sub>5</sub> versus 442 mg kg<sup>-1</sup> in T<sub>1</sub> at 120 DAS), indicating that microbial enrichment enhances P availability while sustaining the overall soil P reserve for subsequent crops.

**Table 5:** Soil inorganic phosphorus fractions (mg kg<sup>-1</sup>) at 120 DAS as influenced by microbial enriched granulated rock phosphate

| Treatment      | Sal-P | Al-P  | Fe-P  | Ca-P  | Red-P | Occ-P | Org-P | Total-P |
|----------------|-------|-------|-------|-------|-------|-------|-------|---------|
| T <sub>1</sub> | 0.60  | 40.8  | 177.4 | 48.2  | 54.2  | 66.8  | 54.0  | 442     |
| T <sub>2</sub> | 2.20  | 76.4  | 152.6 | 87.2  | 50.6  | 59.8  | 76.2  | 505     |
| T <sub>3</sub> | 2.15  | 73.6  | 157.8 | 90.4  | 52.0  | 62.4  | 75.65 | 514     |
| T <sub>4</sub> | 1.98  | 69.8  | 163.2 | 84.0  | 53.8  | 64.6  | 71.62 | 509     |
| T <sub>5</sub> | 5.10  | 122.4 | 96.6  | 136.4 | 22.6  | 30.2  | 107.7 | 521     |
| T <sub>6</sub> | 4.40  | 108.8 | 110.4 | 122.6 | 27.4  | 36.4  | 102.4 | 513     |
| T <sub>7</sub> | 3.60  | 95.2  | 124.8 | 108.6 | 33.4  | 43.8  | 95.6  | 505     |
| T <sub>8</sub> | 2.90  | 82.4  | 139.2 | 94.8  | 40.0  | 51.6  | 86.1  | 497     |
| S.Em±          | 0.14  | 3.25  | 5.62  | 4.08  | 1.83  | 2.35  | 4.16  | 8.95    |
| CD (P=0.05)    | 0.42  | 9.86  | 17.05 | 12.37 | 5.56  | 7.12  | 12.62 | 27.15   |

Treatment codes as in Table 1. Sal-P = Saloid-bound P; Al-P = Aluminium-bound P; Fe-P = Iron-bound P; Ca-P = Calcium-bound P; Red-P = Reductant-soluble P; Occ-P = Occluded P; Org-P = Organic P.

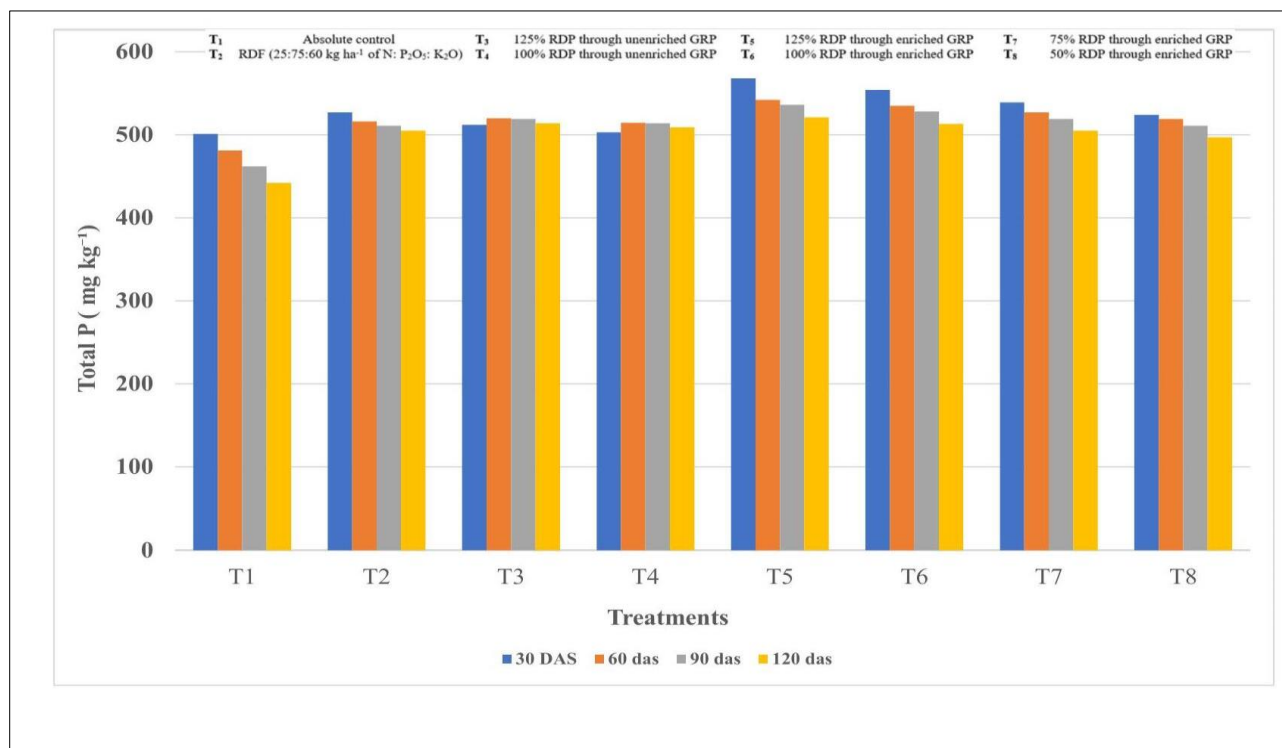


**Fig 7:** Effect of microbial enriched granulated rock phosphate on total soil phosphorus under cluster bean at 30, 60, 90 and 120 DAS

### 3.7 Post-harvest soil fertility status

Post harvest soil pH, EC and organic carbon were not significantly affected by treatment (pH 5.8-6.6; EC 0.116-0.176 dS m<sup>-1</sup>; OC 1.82-2.58%), but available N and K, exchangeable Ca and Mg, and DTPA-extractable Fe, Mn, Cu and Zn were significantly higher under enriched GRP, particularly T<sub>5</sub> (available N 198.4 kg ha<sup>-1</sup>; available K<sub>2</sub>O 354.2 kg ha<sup>-1</sup>; exchangeable Ca 2.74 and Mg 1.08 cmol(p<sup>+</sup>) kg<sup>-1</sup>), against the lowest values in the control (142.4 kg N ha<sup>-1</sup>; 291.2 kg K<sub>2</sub>O ha<sup>-1</sup>). This improvement in residual fertility mirrors the enhanced biological nitrogen fixation, root biomass turnover and rhizosphere organic-acid activity associated with microbial enrichment (Peoples *et al.*, 2009; Haq and Mallarino, 2000; Alloway, 2008) [25, 15, 2], and is agronomically significant for the succeeding crop in the rotation.

### 3.8 Microbial population dynamics during incubation

The clay-humic acid granulated carrier sustained all three inoculated groups PSB, KMB and Azotobacter above the recommended minimum viable count of 10<sup>7</sup> CFU g<sup>-1</sup> for 7-8 weeks, with Azotobacter attaining the highest peak population, followed by PSB and KMB, indicating good adaptability of these organisms to the granule matrix. The initial rise in population up to the third week reflects the favourable moisture buffering and carbon supplementing environment created by the clay-humic acid matrix, while the subsequent decline is attributable to nutrient depletion, moisture loss and intra-consortium competition, a pattern consistent with the survival kinetics reported for Burkholderia sp. on rock-phosphate-based granular carriers (Anandham *et al.*, 2007) [4] and the beneficial role of humic acid in sustaining microbial activity on rock phosphate (Sumreen *et al.*, 2022) [32].

### 4. Conclusion

Microbial enrichment of granulated low-grade rock phosphate with a consortium of phosphate-solubilizing bacteria, potassium-mobilizing bacteria and Azotobacter significantly improved the

growth, yield, nutrient uptake and soil phosphorus status of cluster bean grown in an acidic sandy clay loam soil. Application of just 75 per cent of the recommended dose of phosphorus through enriched GRP (T<sub>7</sub>) produced pod yield and nutrient uptake statistically on par with, and in several respects superior to, 100 per cent RDP through enriched GRP (T<sub>6</sub>), and substantially exceeded the performance of the standard chemical RDF and unenriched GRP at equivalent or even higher doses. Enriched GRP treatments simultaneously reduced soil P-fixing capacity and favourably redistributed soil phosphorus toward labile, plant-available fractions while conserving the overall soil P pool. These findings establish microbially enriched granulated rock phosphate as an agronomically efficient, cost-effective and environmentally sustainable alternative to conventional chemical phosphate fertilizer, capable of reducing chemical P input by up to 25 per cent without compromising cluster bean productivity, with clear relevance for P-deficient acid soils of the hilly zone of Karnataka and similar dryland tracts.

### Acknowledgement

The author gratefully acknowledges the Department of Soil Science, College of Agricultural Sciences, and the Main Agricultural and Horticultural Research Station (MAHRS), Iruvakk, Keladi Shivappa Nayaka University of Agricultural and Horticultural Sciences (KSNUAHS), Shivamogga, for providing the experimental facilities used in this study.

### References

1. Allah Ditta A, Muhammad J, Imtiaz M, Mehmood S, Qian Z, Tu S. Application of rock phosphate enriched composts increases nodulation, growth and yield of chickpea. *Int J Recycl Org Waste Agric*. 2018;7(1):33-40.
2. Alloway BJ. Zinc in Soils and Crop Nutrition. 2nd ed. Brussels and Paris: International Zinc Association and International Fertilizer Industry Association; 2008.
3. Anandham R. Studies on phosphate solubilizing bacteria and their potential for use as biofertilizer [PhD thesis].

- Coimbatore: Tamil Nadu Agricultural University; 2007.
4. Anandham R, Choi KH, Indira Gandhi P, Yim WJ, Park SJ, Kim KA, *et al.* Evaluation of shelf life and rock phosphate solubilization of *Burkholderia* sp. in nutrient-amended clay, rice bran and rock phosphate-based granular formulation. *World J Microbiol Biotechnol.* 2007;23:1121-1129.
  5. Biswas DR, Narayanasamy G. Rock phosphate enriched compost: An approach to improve low-grade Indian rock phosphate. *Bioresour Technol.* 2006;97(18):2243-2251.
  6. Bolan NS, Naidu R, Mahimairaja S, Baskaran S. Influence of low-molecular-weight organic acids on the solubilization of phosphates. *Biol Fertil Soils.* 1994;18(4):311-319.
  7. Bray RH, Kurtz LT. Determination of total organic and available forms of phosphorus in soils. *Soil Sci.* 1945;59:39-45.
  8. Chauhan H, Bagyaraj DJ, Selvakumar G, Sundaram SP. Novel plant growth promoting rhizobacteria: Prospects and potential. *Appl Soil Ecol.* 2017;95:38-53.
  9. Chen YP, Rekha PD, Arun AB, Shen FT, Lai WA, Young CC. Phosphate solubilizing bacteria from subtropical soil and their tricalcium phosphate solubilizing abilities. *Appl Soil Ecol.* 2006;34(1):33-41.
  10. Dhillon J, Torres G, Driver E, Figueiredo B, Raun WR. World phosphorus use efficiency in cereal crops. *Agron J.* 2017;109(4):1670-1677.
  11. Farrag HM, Bakr AAEMA. Effect of applying bio-enriched rock phosphate on soil properties and wheat plant growth. *Egypt J Soil Sci.* 2023;63(1):1-13.
  12. Garg N, Chandel S. Arbuscular mycorrhizal networks: Process and functions. *Agron Sustain Dev.* 2010;30(3):581-599.
  13. Gomez KA, Gomez AA. Statistical Procedures for Agricultural Research. 2nd ed. New York: John Wiley and Sons; 1984.
  14. Grant CA, Flaten DN, Tomasiewicz DJ, Sheppard SC. The importance of early season phosphorus nutrition. *Can J Plant Sci.* 2001;81(2):211-224.
  15. Haq MU, Mallarino AP. Soybean yield and nutrient composition as affected by early season foliar fertilization. *Agron J.* 2000;92(1):16-24.
  16. Hinsinger P. Bioavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: A review. *Plant Soil.* 2001;237(2):173-195.
  17. Jackson ML. Soil Chemical Analysis. New Delhi: Prentice Hall of India Pvt. Ltd.; 1973.
  18. Khan MS, Zaidi A, Wani PA. Role of phosphate-solubilizing microorganisms in sustainable agriculture: A review. *Agron Sustain Dev.* 2007;27(1):29-43.
  19. Kukey RMN, Janzen HH, Leggett ME. Microbially mediated increases in plant-available phosphorus. *Adv Agron.* 1989;42:199-228.
  20. Kumari M, Meena R, Kumar C, Kumar D. Efficacy of rock phosphate enriched compost on growth, yield and uptake of nutrients by summer mung bean (*Vigna radiata* (L.) Wilczek) in inceptisol of Varanasi. *J Eco-friendly Agric.* 2024;19(2):287-293.
  21. Lindsay WL, Norvell WA. Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Sci Soc Am J.* 1978;42(3):421-428.
  22. Meena MD, Biswas DR. Effect of rock phosphate enriched compost and chemical fertilizers on microbial biomass phosphorus and phosphorus fractions. *Afr J Microbiol Res.* 2015;9(23):1519-1526.
  23. Narula N, Kumar V, Behl RK, Deubel A, Gransee A, Merbach W. Effect of P-solubilizing *Azotobacter chroococcum* on N, P, K uptake in P-responsive wheat genotypes grown under greenhouse and field conditions. *J Plant Nutr Soil Sci.* 2000;163(4):393-398.
  24. Penn CJ, Camberato JJ. A critical review on soil chemical processes that control how soil pH affects phosphorus availability to plants. *Agriculture.* 2019;9(6):120.
  25. Peoples MB, Brockwell J, Herridge DF, Rochester IJ, Alves BJR, Urquiaga S, *et al.* The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. *Symbiosis.* 2009;48:1-17.
  26. Pradhan N, Sukla LB. Solubilization of inorganic phosphates by fungi isolated from agricultural soil. *Afr J Biotechnol.* 2006;5(10):850-854.
  27. Sharif M, Burni T, Wahid F, Khan F, Khan S, Khan A, *et al.* Effect of rock phosphate composted with organic materials on yield and phosphorus uptake of wheat and mung bean crops. *Pak J Bot.* 2013;45(4):1349-1356.
  28. Sharma SB, Sayyed RZ, Trivedi MH, Gobi TA. Phosphate solubilizing microbes: Sustainable approach for managing phosphorus deficiency in agricultural soils. *SpringerPlus.* 2013;2(1):587.
  29. Sharma A, Kapoor R. Transformation of inorganic phosphorus fractions in acidic soils as influenced by rock phosphate, farmyard manure and phosphate solubilizing bacteria. *J Indian Soc Soil Sci.* 2016;64(2):128-135.
  30. Singh H, Tripathi AK. Interaction between phosphate solubilizing bacteria and arbuscular mycorrhizal fungi on phosphorus fractions and soil biological properties in an Alfisol. *J Soil Sci Plant Nutr.* 2013;13(4):967-979.
  31. Subbaiah BV, Asija GL. A rapid method for the estimation of available nitrogen in soils. *Curr Sci.* 1956;25:259-260.
  32. Sumreen S, Sharif M, Sultan T, Ali I. Effect of rock phosphate augmented with humic acid on phosphorus uptake and yield of wheat (*Triticum aestivum* L.). *Pak J Agric Res.* 2022;35(2):417-424.
  33. Vassilev N, Vassileva M, Azcon R, Medina A. Interactions of an arbuscular mycorrhizal fungus with *Aspergillus niger* on plant growth and P-uptake. *Appl Microbiol Biotechnol.* 2001;59(1):1-4.
  34. Walkley A, Black IA. An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 1934;37(1):29-38.
  35. Yadav BK, Tarafdar JC. *Penicillium purpurogenum*, unique P mobilizer in arid agroecosystems. *Arid Land Res Manag.* 2011;25(1):87-99.