

Original Research Article

Inference of Rock Phosphate, Phosphorus Solubilizing Bacteria, and Lime on phosphorus content and Economic yield of green gram

Abstract

Aim: To study the effect of Rock Phosphate, Phosphorus Solubilizing Bacteria, and Lime on phosphorus content in the soil, Phosphorus Uptake, and Economic yield of green gram (var. DGGGS-4).

Study design: This experiment was conducted through a completely randomized design with 10 treatments and 3 replications.

Place and Duration of Study: The research was conducted at the Department of Soil Science and Agricultural Chemistry, Central Agricultural University, Imphal between February 2019- November 2019.

Methodology: Available phosphorus content in soil was estimated spectrophotometrically by Bray and Kurtz No. 1 method, the Active Phosphorus was determined by the addition of Saloid-bound phosphate, Aluminium phosphate, iron phosphate, and calcium phosphate, and total Inorganic P is the summation of all the inorganic forms of P. Total Phosphorus (Total P) in Soil was estimated by using Murphy-Riley solution and 5M NaOH and the intensity of yellow color was read at 730 nm in a spectrophotometer, organic P was calculated from the difference between total phosphorus and total mineral P, and the uptake of phosphorus was computed from the data on P concentration and dry matter yield.

Results: The release and fixation pattern of different forms of phosphorus, its uptake, and the economic yield of green gram were significantly affected by the application of rock phosphate ~~either singly or in combination~~ singly or combined with Phosphorus Solubilizing Bacteria and lime. Comparing among the different treatments, significantly higher accumulation of ~~a~~ available Phosphorus, ~~and~~ Phosphorus uptake, and economic yield were recorded in soil treated with Rock phosphate in combination with *Phosphocare*, *Bacillus megatherium*, and lime which is at par with treatment with Rock phosphate in combination with *Bacillus megatherium* and lime.

Conclusion:The investigation revealed that the release and fixation pattern of different forms of phosphorus, its uptake, and [the](#) yield of green gram are significantly affected by the application of RP ~~either singly or in combination~~[singly or combined](#) with PSB and lime.

Keywords:Phosphorus, Phosphorus Solubilizing Bacteria, lime, ~~and~~Rock phosphate,~~and~~ Economic Yield.

1. Introduction

The word Phosphorus is taken from Greek, the word *phos* means light, and *phoros* means bearer. The word Phosphorus itself gives ~~a~~ meaning that it glows because of its slow combustion when it comes in contact with the air. It was discovered in ancient Rome ~~than~~ [and](#) through [the](#) ages it lost its secret, but this is a mystery. It was discovered by German alchemist Henning Brandt in 1669 [1].

Phosphorus is the second essential nutrient for plants next to nitrogen. It is absorbed by the plants in two forms HPO_4^{2-} and H_2PO_4^- . It is also known as the key to life because the plant life cycle cannot complete due to its deficiency. It influences ~~the~~ plant metabolic processes like signal transduction, photosynthesis, respiration, transport, and storage of energy in the form of ATP and ADP [2]. Various forms of Al, Fe, Mg, ~~and~~ Ca elements [combine with inorganic phosphorus, making](#) ~~combines with inorganic phosphorus and make~~ it unavailable for plants and microbes. The organic Phosphorus which is in unavailable form for plants is converted to available form by soil microbes and enzymes released by the plant roots through mineralization processes. Soil P is a finite, non-renewal, and limited resource, and the reserves of P in the world are gradually being depleted [3]. Only 10-20% of the P applied with fertilizer is taken up by plants in the year of application because the majority of applied P is rapidly fixed or precipitated into poorly available forms [4]. The uptake of P from colloidal Al-P is considerably higher than colloidal Fe-P in acid soil which is due to a faster rate of crystallization of Fe-P than Al-P and ~~a~~ greater reduction in [the](#) surface area [5]. In India~~n~~, the iron-P and aluminum-P were higher in the recent alluvial soils than in old~~s~~ alluvial [6].

In the present agricultural scenario, the high cost of conventional water-soluble phosphatic fertilizers like SSP and DAP restricts their use in developing countries like India. Thus, phosphatic fertilizers can be substituted by rock phosphates. Crop response to phosphate

rock application ~~strongly depends upon rock dissolution rate~~ ~~is strongly dependent upon the rate of dissolution of rock~~ [7]. The phosphate rock can be recommended for direct use as it is economic, has a longer residual effect, and has potential use in plantation and long duration crops, minimizes phosphorus fixation in acid soils, has considerable liming action by reducing soil acidity, increases the availability of other essential nutrient elements including calcium to plants [8]. Phosphorus availability can be improved from rock phosphate by using microbial processes [9].

Non-symbiotic bacteria which are closely associated with plant roots improve the growth and development of plants by different mechanisms and are called plant growth-promoting rhizobacteria [10, 11, 12]. PSB plays a sustainable and environmentally friendly role in dissolving phosphatic fertilizers and bound phosphorus thereby enhancing plant growth, phosphorus uptake, and yield [13, 14, 15, 16]. In India 49 million ha of acid below 5.6 pH and 23 million ha between 5.6 pH and 6.5 pH [17]. To overcome the problem of low Phosphorus availability due to high phosphorus fixation, the suggested approaches are a selection of suitable crops adaptive to soil acidity [18] and amelioration of soil acidity through liming [19]. Liming improves the base saturation of the soil, increases the soil pH to near neutrality, inactivates Al, Fe, and Mn, reduces P fixation [20], and stimulates microbial activity leading to the mineralization of organic nitrogen and fixation of atmospheric nitrogen. There is a need for raising the soil pH beyond the point of neutralizing exchangeable aluminum, particularly for legumes [21].

Green gram (*Vigna radiate* L.) is popularly known as "Moong Dal" in India and is a tiny ~~circular-shaped~~ circular-shaped bean that is green in color. It is one of the main pulse crops in India. It belongs to the family Leguminosae and the sub-family subfamily Papilionaceae. It is an erect sub-erect deep-rooted, much-branched, somewhat hairy annual herb with a height ranging from 30-130 cm. Leaves are alternate, trifoliate, petiole long, stipules ovate, leaflets ovate up to 12x10 cm. Flowers are in axillary racemes, peduncles s up to 13 cm in length with clusters of 10-12 flowers, corolla yellow in color sometimes curved, 5-10 cm long. The seeds contain a higher proportion of lysine than any other legume seeds. The seeds are processed and consumed as cooked whole beans or splits (dhals), sprouts, immature seeds, and flour and are used in various recipes.

2. Materials and Methods

During the *Pre-Kharif* season of 2021, the investigation was conducted in pots at the Department of Soil Science and Agricultural Chemistry, College of Agriculture, CAU, Imphal to investigate the effect of applied rock phosphate in the presence or absence of phosphorus solubilizing bacteria and lime on phosphorus content and economic yield of Green Gram (var. DGGS-4). The experiment was conducted in a completely randomized block design replicated thrice. The treatments were as follows:

- T₁ = Control
- T₂ = 100 % RD* of P₂O₅ from SSP*
- T₃ = 100 % RD of P₂O₅ from RP*
- T₄ = 100 % RD of P₂O₅ from RP + PSB₁*
- T₅ = 100 % RD of P₂O₅ from RP + PSB₂*
- T₆ = 100 % RD of P₂O₅ from RP + PSB₁ + PSB₂
- T₇ = 100 % RD of P₂O₅ from RP + Lime
- T₈ = 100 % RD of P₂O₅ from RP + PSB₁ + Lime
- T₉ = 100 % RD of P₂O₅ from RP + PSB₂ + Lime
- T₁₀ = 100 % RD of P₂O₅ from RP + PSB₁ + PSB₂ + Lime

*SSP - Single Super Phosphate

*PSB - Phosphorus Solubilizing Bacteria

*RP - Rock Phosphate

*RD- Recommended Dose

* PSB₁ – *Phosphocare*

* PSB₂ – *Bacillus megatherium*

Each of the pots was filled with 5 Kg of ~~air-dried~~ air-dried soil. In each experimental pot, a recommended dose of 20 kilograms of N ha⁻¹ in the form of urea and 20 kg of K₂O ha⁻¹ in the form of ~~muriate-muriaticof~~ potash was applied and thoroughly mixed with the soil. Rock phosphate and SSP were administered to the pots as phosphorus sources according to different sets of treatments based on the prescribed amount (40 kg P₂O₅ ha⁻¹) for the test crop Greengreen gram (variety DGGS-4). Two PSBs were used to treat green gram seeds. PSB₁ (Commercial) strain from the market and PSB₂ strain from the lab (*Bacillus megatherium*). The inoculated seeds were dried in the shade and sowed as soon as they were dry. In each pot, five green gram seeds were sowed. Following germination, a single seedling was retained throughout the

Comment [M1]: For how long?? [dried]

experiment. The soils of each treatment were humidified at 60% of the [water holding water-holding](#) capacity during the entire experiment.

The soil samples were collected on the 0th, 15th, 30th, 45th, and 60th days after sowing seeds and at harvest from the rhizosphere region of a green gram to estimate the phosphorus content. The lime requirement is calculated by SMP (Shoemaker Mclean Pratt) buffer method [22], two weeks before liming is done to the soil so that it reacts with soil mass according to different sets of treatments. The pH of the soil was estimated by using a glass electrode Systronic pH meter with a water suspension ratio of 1:2.5 as described by [23].

Available phosphorus content in soil was estimated spectrophotometrically by Bray and Kurtz No. 1 method as described by [24]. The whole seeds were used to record the economic yield after drying at 65 to 70°C to constant dry weight. The economic yield was recorded and expressed in grams per plant.

2.1 Active P

The Active Phosphorus was determined by the addition of Saloid-bound phosphate, Aluminium phosphate, iron phosphate, and calcium phosphate [25].

2.2 Total Inorganic P

Inorganic P is the summation of all the inorganic forms of P.

2.3 Total Phosphorus (Total P) in Soil

Two grams of 0.5 mm sieved soil [were as](#) weighed and transferred to a 300 ml platinum crucible and 30 ml of 60 percent HClO₄ was added and digestion was carried out on a sand bath at 150°C till the dense fumes of HClO₄ evolved. When digestion was completed, the flask was removed and cooled. 50 ml of distilled water was added to the flask and the solution was filtered into a 250 ml volumetric flask and volume was made with distilled water. An aliquot from this was used for estimation of total P by using Murphy-Riley solution and 5M NaOH and the intensity of yellow color was read at 730 nm in a spectrophotometer [23].

2.4 Organic Phosphorus

The organic P was calculated from the difference between total phosphorus and

total mineral P as suggested by [26].

2.5 Phosphorus Uptake

The uptake of phosphorus was computed from the data on P concentration and dry matter yield using the formula

$$\text{P uptake in plant (mg plant}^{-1}\text{)} = \text{P conc.in plant (mg kg}^{-1}\text{)} \times \text{dry matter yield (g plant}^{-1}\text{)} \times (1/1000)$$

Data obtained from the experiment were statistically analyzed through [the](#) analysis of variance technique for comparing the effects of the treatments. The significance of various effects was tested at a 5% level of probability [27].

3. Results and Discussion

3.1 Active-P

Data on the amount of Active-P in green gram grown in soil fertilized with rock phosphate in the presence or absence of PSB and lime are illustrated in ([Figure1](#)). Results signified that an increasing trend of Active - P up to [the](#) 30th day followed by a decline till harvest was observed in all the treatments except in T₄ where it increases at [the](#) 15th day and reduces till harvest. This increase might be due to the transformation of applied P into less soluble forms showing that the P fixing capacity of the soil increases [28, 29, 30]. However, the decrease in the concentration might be due to crop utilization [31, 32, 33, 34, 35]. ~~Critical-A critical~~ study of the data showed that irrespective of different treatments and crop growth stages significantly higher Active-P was accumulated more in rock phosphate fertilized soil in the presence or absence of PSB and lime over untreated control. ~~Similar findings were recorded by This is at similarity with the findings of~~ Tiecher, Dos Santos, and Calegari [36] and Tian [37]. Among all the treatments most significant treatment is T₃ followed by T₄ and T₂ on [the](#) 60th day and at harvest. Comparatively, [a](#) higher concentration of Active-P was observed in soil treated with T₄ which is at par with T₃ and T₆ on the 15th and 30th days after sowing, respectively. The treatments which are applied with PSB and lime show significantly lesser concentrations of Active-P compared with rock ~~phosphate added phosphate-added~~ soil without lime and PSB. The addition of PSB and lime reduces P fixation in soil.

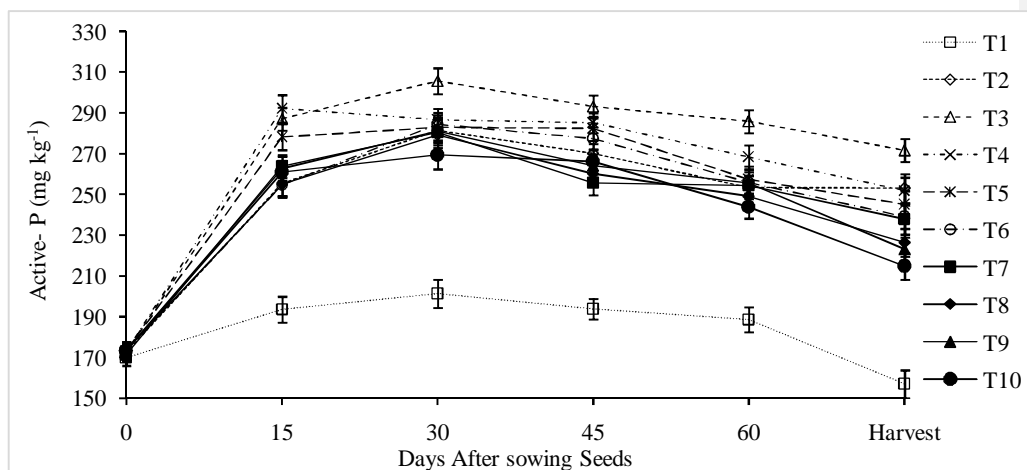


Figure 1: Changes in Active- P (mg kg^{-1}) the content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of the mean)

3.2 Total Inorganic –P

Data illustrated in (Figure 2) show changes in the amount of total Inorganic-P in green gram grown in soil added with rock phosphate, PSB, and lime. Results revealed that Inorganic-P content increased up to the 30th day and decline till harvest in all the treatments except in T₁, T₅, T₆, and T₁₀ which shows an increase up to the 45th day and decrease till harvest. The increasing trend might be due to the transformation of applied P or organic P to inorganic forms [28][29][30]. The decline might be due to the release of these forms into available P and finally, uptake by green gram [33][34]. Statistically more accumulation of total Inorganic-P was observed in all treatments with respect to control at different stages of crop growth. Similar- A similar finding on higher content of total Inorganic-P in P-treated soil was also reported by Jalali and Ranjbar and others [38, 36, 30, 37]. Among all the treatments, T₄ shows the maximum amount of total inorganic P followed by T₃ and T₂ on the 30th day and at harvest, respectively. No significant difference was observed between T₄ and T₃ on the 15th, 45th, and 60th days.

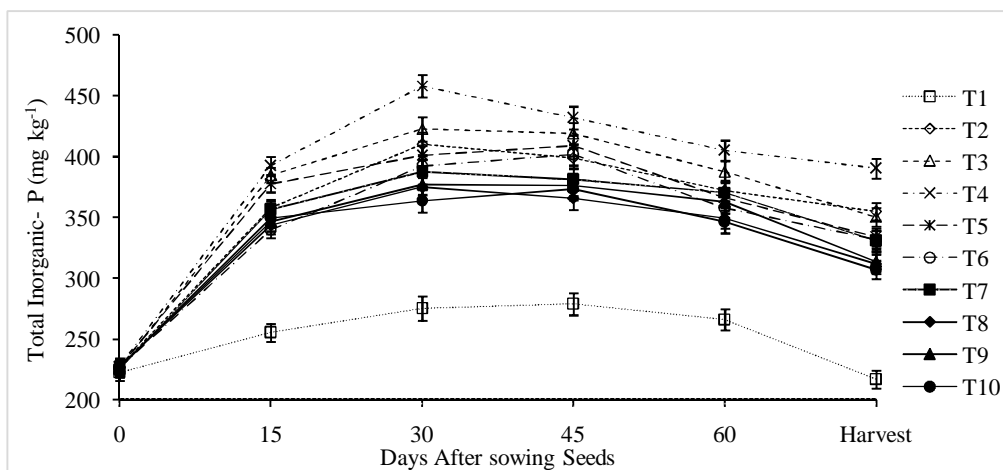


Figure 2: Changes in Total Inorganic- P (mg kg⁻¹) the content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of the mean)

3.3 Available-P

Data on changes in the amount of Available-P in green gram grown in soil added with rock phosphate, PSB, and lime were shown in (Figure 3). Available-P concentration reached a maximum on the 30th day followed by a decline up to harvest in all the treatments. The increase indicated the release of phosphorus into the available form [39, 40, 41]. The decrease might be due to the fixation/adsorption of phosphorus onto Fe and Al oxides in acid soils and by the formation of Fe and Al phosphate complexes [42] or phosphorus uptake by crops [33, 34]. Further, the results revealed that irrespective of different treatments and sampling stages, there was a significant increase in available P in rock phosphate fertilized soil in the presence or absence of PSB and lime over control. This is at par with the findings of Singh [43], Jalali and Ranjbar [38], and Wang [44]. An increase in phosphorus availability due to rock phosphate application was also reported earlier by Laskar[39]. The detailed study revealed that the maximum amount of available P was recorded in T₁₀ followed by T₉ on the 15 and 30th day. Comparatively A comparatively higher concentration of Available-P was found in T₁₀ sowing parity with T₉ and T₈ on the 45th day and at harvest. Irrespective of different sampling stages treatments applied along with lime show a significantly higher concentration of Available-P over unlime treatments. This shows that liming can increase phosphorus availability by stimulating the

mineralization of soil organic phosphorus [45, 46]. It was also observed that irrespective of liming, the addition of PSB comparatively enhanced available P content over sole rock phosphate treatment from the 30th day onwards till harvest, and similar results were obtained by Sundra, Natarajan, and Hari[47]. PSB plays an important role in dissolving both fertilizer phosphorus and bound P in the soil that is environmentally friendly and sustainable. P solubilization is mainly due to the reaction between organic acids executed with phosphate binders such as Al, Fe, and Ca, or Mg to form stable organic chelates to free the bound phosphate ion [13].

Figure 3: Changes in Available P (mg kg^{-1}) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of mean)

3.4 Organic-P

Data on changes in the amount of Organic P in green gram grown in soil applied with rock phosphate, PSB, and lime was illustrated in (figure 4). Results revealed that irrespective of different treatments Organic P concentration declined at harvest as compared with the initial value. This shows the mineralization of Organic P [48]. Higher amount of Organic P was

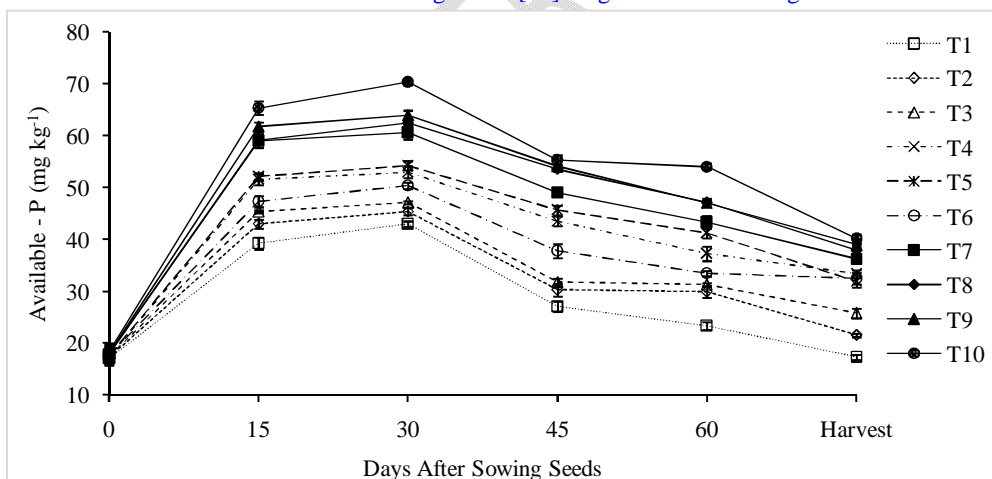


Figure 3: Changes in Available P (mg kg^{-1}) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of the mean)

3.4 Organic-P

Data on changes in the amount of Organic P in green gram grown in soil applied with rock phosphate, PSB, and lime was illustrated in (Figure 4). Results revealed that

irrespective of different treatments Organic-P concentration declined at harvest as compared with the initial value. This shows the mineralization of Organic-P [48]. A higher amount of Organic-P was accumulated in untreated soil when compared to phosphorus-treated soil except at zero days of sowing. This might be due to a higher rate of P-mineralization in soil treated with RP as compared to untreated soil [48]. In general, treatments that are applied along without lime show significantly lesser Organic-P over the treatments which are applied with lime on the 30th day. Irrespective of liming, rock phosphate applied with gave a significantly lesser concentration of Organic-P over the treatments without PSB at harvest. Comparing among the lime-treated system at harvest combined application of PSB₁ and PSB₂ recorded lower organic P content. Reports are also given that mixed inoculations of phosphate-solubilizing microorganisms enhanced the mineralization of organic phosphate [49, 50].

Figure 4: Changes in Organic P (mg kg^{-1}) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of mean)

3.5 Total Phosphorus (P) in Soil

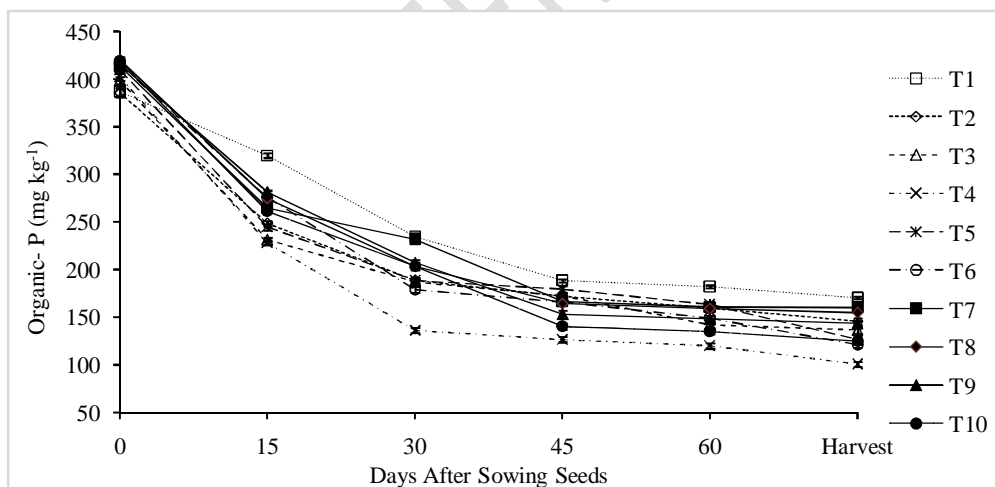


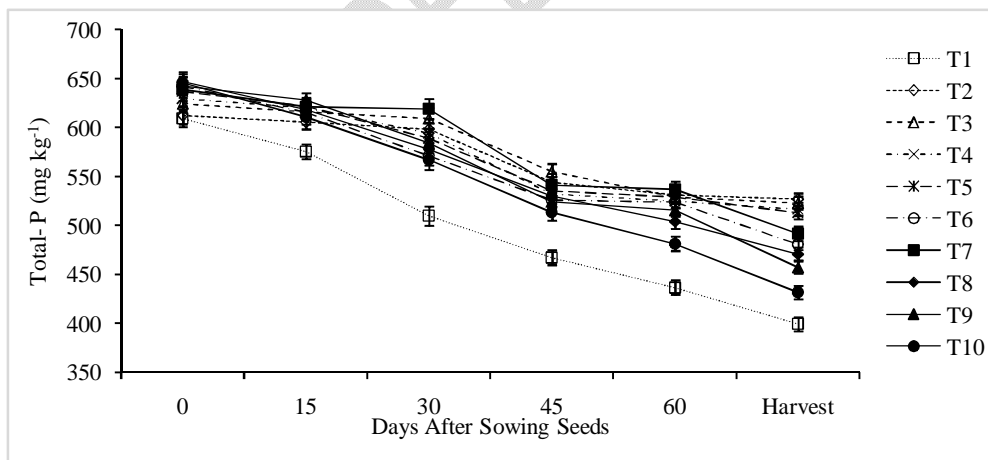
Figure 4: Changes in Organic P (mg kg^{-1}) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of the mean)

3.5 Total Phosphorus (P) in Soil

Data on changes in Total-P concentration in green gram grown in soil added with rock phosphate, PSB, and lime were illustrated in (Figure 5). The data revealed that irrespective of different treatments and sampling stages Total-P declined gradually till harvest. Total-P was recorded more in P treatments when compared to control at different stages of crop growth. Similar reports were also presented earlier by [44, 51, 36]. Irrespective of lime and PSB addition no significant difference in Total-P value was recorded in RP-treated soils on the 15th, 30th, 45th, and 60th DAS. However, further study of the data revealed that a statistically higher content of Total-P was found in T₇ followed by T₈ at harvest. The treatments applied along with lime shown showed significantly lesser accumulation of Total-P compared to the corresponding similar treatment without lime at harvest. It was also observed that comparing between the RP-treated soils with or without lime separately, soil applied with the two PSBs in the combination shown showed significantly fewer concentrations of total P over non-PSB and single PSB treatments at harvest.

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Figure 5: Changes in Total P (mg kg⁻¹) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of mean)



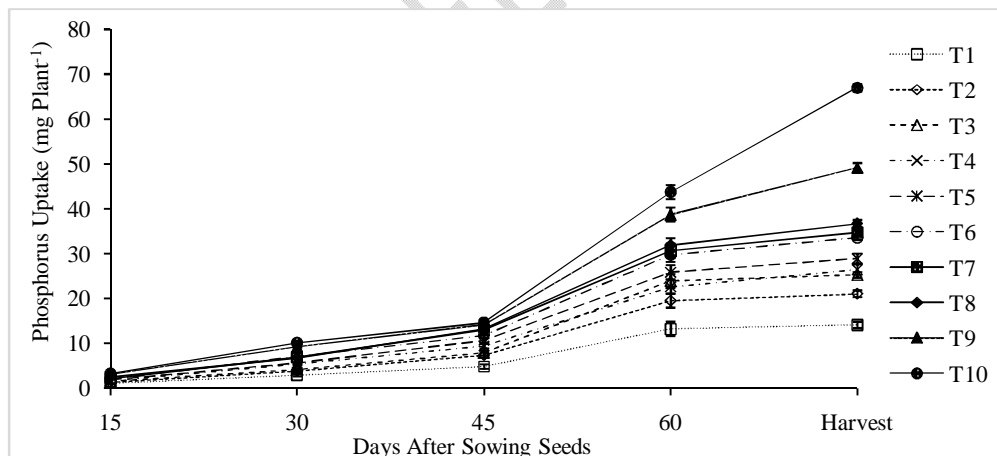
3.6 P-Uptake

Figure 5: Changes in Total P (mg kg⁻¹) content in green gram grown in rock phosphate fertilized soil applied with PSB and lime (error bar shows the standard error of the mean)

3.6 P-Uptake

Data on P-Uptake by green gram grown in soil fertilized with rock phosphate in the presence or absence of PSB and lime are illustrated in (Figure 6). The data revealed that irrespective of different treatments there was an increasing trend of P-uptake by green gram up to harvest. This increase in uptake with crop age was examined earlier by Ikerra, Mkeni, and Singh [52] and Setia and Sharma [53]. Statistically higher amount of P-uptake was observed in all P treatments when compared to control at different crop growth stages. This is at par with the reported findings of [31, 33]. Further investigation signified that significantly higher P uptake by green gram was found in T₁₀ which is followed by T₉ on the 30th and 60th day and at harvest. On the 15th and 45th DAS, comparatively higher P uptake was found in soil applied with T₁₀ which is statistically at par with T₉. Comparing between RP-added limed and unlimed treated systems, it was found that liming significantly increased P-uptake over related similar treatments without lime.

Figure 6: Phosphorus Uptake (mg Plant^{-1}) by green gram grown in rock phosphate fertilized soil applied with phosphorus solubilizing bacteria and lime (error bar shows the



standard error of mean)

Figure 6: Phosphorus Uptake (mg Plant^{-1}) by green gram grown in rock phosphate fertilized soil applied with phosphorus solubilizing bacteria and lime (error bar shows the standard error of the mean)

3.7 Economic Yield

Data pertaining to the Economic Yield of green gram grown in soil fertilized with rock phosphate in the presence or absence of PSB and lime were illustrated in (Figure 7). The result revealed that a statistically higher yield was recorded in green gram grown in P-treated systems as compared to the control. This is at par with the several records of [54, 33, 55, 15, 35]. Statistically, the maximum economic yield was found in soil treated with T₁₀ showing parity with T₉ and T₈. RP-treated soil applied with lime gave statistically more yield when compared to the remaining unlimed treatments. This shows that RP applied with PSB and lime gave a higher economic yield than the unlimed soils.

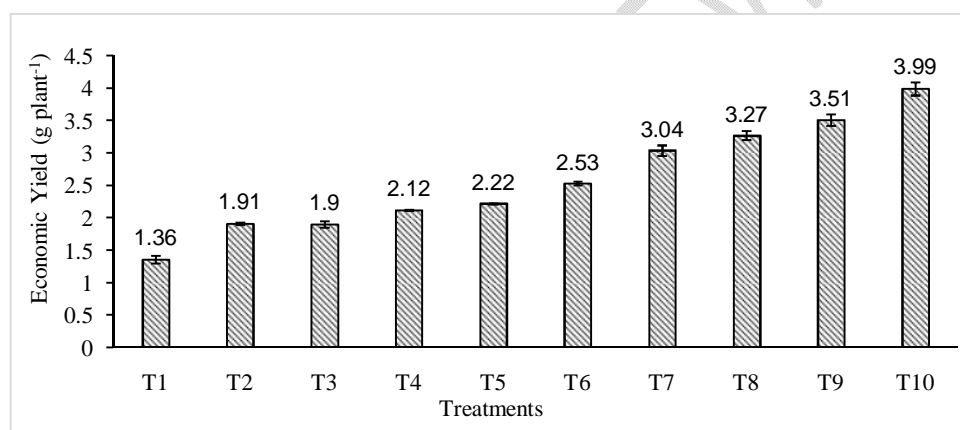


Figure 7: Economic Yield (g Plant⁻¹) of green gram grown in rock phosphate fertilized soil applied with phosphorus solubilizing bacteria and lime (error bar shows the standard error of the mean)

4. Conclusion

Irrespective of the different treatments and sampling stages, all the P treatments showed higher accumulation of active P, total inorganic P, available P, P uptake, and economic yield when compared to the control whereas total P and Organic P reduces. The treatment which includes the combination of 'RP+PSB+lime' showed statistically more accumulation of available P, P uptake, and economic yield of green gram. Application—The application of phosphorus

sources results in accelerating different forms of P content in the soil. Among different treatments increased P-uptake and economic yield was seen more in Rock phosphate applied along with PSB and lime. The investigation revealed that the release and fixation pattern of different forms of phosphorus, its uptake, and [the yield of a green gram](#) are significantly affected by the application of RP [either singly or in combination singly or combined](#) with PSB and lime.

References

1. Emsley J. The Sordid Tale of Murder, Fire, and Phosphorus. The 13th Element. London, England: Macmillan Publishers; 2000.
2. Griffith B. Phosphorus. In: Efficient Fertilizer Use Manual. 4th ed. Bannockburn: International Minerals and Chemical Corporation; 1999.
3. Tiessen H. Introduction and synthesis. Scope-scientific committee on problems of the environment international council of scientific unions. 1995;54:1-6.
4. Vu DT, Tang C, Armstrong RD. Changes and availability of P fractions following 65 years of P application to a calcareous soil in a Mediterranean climate. Plant and Soil. 2008;304(1):21-33. <https://doi.org/10.1007/s11104-007-9516-x>
5. Pattanayak SK, Sureshkumar P, Tarafdar JC. New vista in phosphorus research. Journal of the Indian Society of Soil Science. 2009;57(4):536-45.
6. Rai RN, Prasad RN. Forms of soil phosphorus and suitable extractants for available phosphorus in acid soils of Sikkim. Journal of the Indian Society of Soil Science. 1990;38(2):237-42.
7. Olsen RA. Rate of dissolution of phosphate from minerals and soils. Soil Science Society of America Journal. 1975;39(4):634-39. <https://doi.org/10.2136/sssaj1975.03615995003900040020x>
8. Kisitu VB. Some aspects of using rock phosphate as direct application fertilizers. Fertilizer Research. 1991;30(2):191-92.
9. Zapata F, Axmann H. 32 P isotopic techniques for evaluating the agronomic effectiveness of rock phosphate materials. Fertilizer Research. 1995;41(3):189-95. <https://doi.org/10.1007/BF00748308>

10. Kloepper JW, Scher FM, Laliberte M, Tipping B. Emergence promoting rhizobacteria: Description and implication for agriculture. In: Iron, Siderophores and Plant Diseases. Swinburne, T.R., Eds. Plenum Press. New York, USA. 1986;55-164.
11. Kijne JW, Lugtenberg BJJ, Smit G. Attachment, lectin and initiation of infection in Bradyrhizobium-legume interactions. In: Molecular signals in plant-microbe communications. D. P. S. Verma (ed.). 281-294. CRC Press, Boca Raton;1992.
12. Asghar HN, Zahir ZA, Arshad M. Screening rhizobacteria for improving the growth, yield and oil content of canola (*Brassica napus* L.). Australian Journal of Agricultural Research. 2004;5:187-94.
13. Khan MS, Zaidi A, Wani PA. Role of phosphate-solubilizing microorganisms in sustainable agriculture. A Review. Agronomy for Sustainable Development. 2007;27:29-43. https://doi.org/10.1007/978-90-481-2666-8_34
14. Swamy CAK, Raghunandan BL, Chandrashekhar M, BrahmaPrakash GP. Bio-activation of rock phosphate vis-a-vis seed treatment with phosphorus solubilizing microbes (PSM) in enhancing P nutrition in cowpea and ragi. Indian Journal of Science and Technology. 2010;3(7):689-92.
15. Rajapaksha RMCP, Herath D, Senanayake AP, Senevirathne MGTL. Mobilization of Rock Phosphate Phosphorus through Bacterial Inoculants to enhance Growth and Yield of Wetland Rice. Communications in Soil Science and Plant Analysis. 2011;42:301-14. <https://doi.org/10.1080/00103624.2011.539084>
16. Yadav J, Yadav S, Singh SG. Plant growth promotion in wheat crop under environmental condition by PSB as bio-fertilizer. Indian Journal of Agricultural Research. 2011;2:76-78.
17. Panda N. Fertilizer management in acid soils for increased efficiency. Fert News. 1979;24:75-83.
18. Foy CD. Physiological effects of hydrogen, aluminum, and manganese toxicities in acid soil. In: Adams, 1st edition. Soil acidity and liming. American Society of Agronomy, Madison. 1984;57-98. <https://doi.org/10.2134/agronmonogr12.2ed.c2>
19. Kamprath EJ. Soil Acidity and Liming: Adams Agronomy 12. 2nd ed. American Society of Agronomy. Madison, Wisconsin; 1984.

20. Dwivedi GK. Tolerance of some crops to soil acidity and response to liming. *Journal of the Indian Society of Soil Science*. 1996;44(4):736-41.
21. Kamprath EJ. Exchangeable aluminum as a criterion for liming leached mineral soils. *Soil Science Society of America Journal*. 1970;34(2):252-54.
<https://doi.org/10.2136/sssaj1970.03615995003400020022x>
22. Shoemaker HE, McLean EO, Pratt PF. Buffer methods for determining lime requirement of soils with appreciable amounts of extractable aluminum. *Soil Science Society of America Journal*. 1961;25(4):274-77.
<https://doi.org/10.2136/sssaj1961.03615995002500040014x>
23. Jackson ML. *Soil Chemical Analysis*. Prentice Hall of India. New Delhi; 1973.
24. Bray RH, Kurtz LT. Determination of total, organic and available forms of phosphorus in soils. *Soil Science*. 1945;59:39-45.
25. Sharma CM, Sangrai AK. Dissolution and transformation of indigenous rock phosphates in an acid Alfisol. *Journal of the Indian Society of Soil Science*. 1993;41(3):447-451.
26. Mehta NC, Legg JO, Goring CAI, Black CA. Determination of organic phosphorus in soils: I. Extraction method. *Soil Science Society of America Journal*. 1954;18(4):443-49.
<https://doi.org/10.2136/sssaj1954.03615995001800040023x>
27. Gomez KA, Gomez AA. *Statistical procedures for agricultural research*. John Wiley and Sons, New York. 1984;8-20.
28. Yin Y, Liang CH. Transformation of phosphorus fractions in paddy soil amended with pig manure. *Journal of Soil Science and Plant Nutrition*. 2013;13(4):809-18.
<http://dx.doi.org/10.4067/S0718-95162013005000064>
29. Mairan NR, Dhawan AS. Fractions of phosphorus as influenced by organic and inorganic sources of nutrients under different cropping systems in vertisol. *Asian Journal of Soil Science*. 2014;9(1):11-15.
30. Manimaran M. Dynamics of phosphorus in soil under the influence of inorganic phosphorus supply. *International Journal of Current Research and Review*. 2014;12:79-80.
31. Misra UK, Das N, Pattanayak SK. Fertilizer value of indigenous phosphate rock modified by mixing with pyrite and composting with paddy straw. *Journal of the Indian Society of Soil Science*. 2002;50(3):259-64.

32. Afzal AFTAB, Ashraf M, Asad SA, Farooq M. Effect of phosphate solubilizing microorganisms on phosphorus uptake, yield and yield traits of wheat (*Triticum aestivum* L.) in rainfed area. *International Journal of Agriculture and Biology*. 2005;7(2):207-09.
33. Majumdar B, Venkatesh MS, Kumar K. Effect of rock phosphate, superphosphate and their mixtures with FYM on soybean and soil-P pools in a typic hapludalf of Meghalaya. *Journal of the Indian Society of Soil Science*. 2007;55(2):167-74.
34. Mashori NM, Memon M, Memon KS, Kakar H. Maize dry matter yield and P uptake as influenced by rock phosphate and single super phosphate treated with farm manure. *Soil and Environment*. 2013;32(2):130-34.
35. Deshpande AN, Dalavi SS, Pandey SH, Bhalerao VP, Gosavi AB. Effect of rock phosphate along with organic manures on soil properties, yield and nutrient uptake by wheat and chickpea. *Journal of the Indian Society of Soil Science*. 2015;63(1):93-99. <http://dx.doi.org/10.5958/0974-0228.2015.00013.4>
36. Tiecher T, Dos Santos DR, Calegari A. Soil organic phosphorus forms under different soil management systems and winter crops in a long term experiment. *Soil and Tillage Research*. 2012;124:57-67. <https://doi.org/10.1016/j.still.2012.05.001>
37. Tian J, Boitt G, Black A, Wakelin S, Condrón LM, Chen L. Accumulation and distribution of phosphorus in the soil profile under fertilized grazed pasture. *Agriculture, Ecosystems and Environment*. 2017;239:228-35. <https://doi.org/10.1016/j.agee.2017.01.022>
38. Jalali M, Ranjbar F. Ageing effects on phosphorus transformation rate and fractionation in some calcareous soils. *Geoderma*. 2009;155:101-06. <https://doi.org/10.1016/j.geoderma.2009.11.030>
39. Laskar BK, De GK, Debnath NC, Basak RK. Phosphorus availability and transformation from Mussoorie rock phosphate in acid soils. *Ecology, Environment and Conservation*. 1990;8:612-16.
40. Kundu S, Basak RK. Effect of the mixture of rock phosphate and superphosphate on available phosphorus in a *VerticOchrequalf*. *Journal of the Indian Society of Soil Science*. 1999;47(3):402-96.

41. Wang Y, Zhang Y. Soil inorganic phosphorus fractionation and availability under greenhouse subsurface irrigation. *Communications in Soil Science and Plant Analysis*. 2012;43:519-32. <https://doi.org/10.1080/00103624.2012.639430>
42. Gerke J. Orthophosphate and organic phosphate in the soil solution of four sandy soils in relation to pH: Evidence for humic-Fe (Al) phosphate complexes. *Communications in Soil Science and Plant Analysis*. 1992;23:601-12. <https://doi.org/10.1080/00103629209368612>
43. Singh M, Reddy KS, Singh VP, Rupa TR. Phosphorus availability to rice (*Oryza sativa* L.) wheat (*Triticum aestivum* L.) in a vertisol after eight years of inorganic and organic fertilizer additions. *Bioresource technology*. 2007;98(7):1474-81. <https://doi.org/10.1016/j.biortech.2006.02.045>
44. Wang W, Chen W, Wang K, Xie X, Yin C, Chen A. Effects of long-term fertilization on the distribution of carbon, nitrogen and phosphorus in water-stable aggregates in paddy soil. *Agricultural Sciences in China*. 2011;10(12):1932-1940. [https://doi.org/10.1016/S1671-2927\(11\)60194-6](https://doi.org/10.1016/S1671-2927(11)60194-6)
45. Haynes RJ. Effects of liming on phosphate availability in acid soils. *Plant and Soil*. 1982;68(3):289-308. <https://doi.org/10.1007/BF02197935>
46. Singh RN, Diwarkar DPS. Transformation of added phosphorus in some Alfisols and Vertisols. *Journal of Research, Birsa Agricultural University*. 2002;14(2):159.
47. Sundra B, Natarajan V, Hari K. Influence of phosphate solubilizing bacteria on the changes in soil available phosphorus and sugarcane and sugar yields. *Field Crops Research*. 2002;77:43-49. [https://doi.org/10.1016/S0378-4290\(02\)00048-5](https://doi.org/10.1016/S0378-4290(02)00048-5)
48. Pramanik P, Bhattacharya S, Bhattacharyya P, Banik P. Phosphorous solubilization from rock phosphate in presence of vermicomposts in Aqualfs. *Geoderma*. 2009;152(1-2):16-22. <https://doi.org/10.1016/j.geoderma.2009.05.013>
49. Molla MAZ, Chowdhury AA, Islam A, Hoque S. Microbial mineralization of organic phosphate in soil. *Plant and soil*. 1984;78(3):393-99. <https://doi.org/10.1007/BF02450372>
50. Adhikari T, Kundu S, Rao AS. Microbial solubilization of phosphorus from nano rock phosphate. *Journal of Agricultural Science and TechnologyA*. 2014;4(6A).

51. Lee CH, Park CY, Park KD, Jeon WT, Kim PJ. Long-term effects of fertilization on the forms and availability of soil phosphorus in rice paddy. *Chemosphere*. 2004;56(3):299-304. <https://doi.org/10.1016/j.chemosphere.2004.02.027>
52. Ikerra TWD, Mnkeni PNS, Singh BR. Effects of added compost and farmyard manure on P release from Minjingu phosphate rock and its uptake by maize. *Norwegian Journal of Agricultural Sciences*. 1994;8(1):13-23.
53. Setia RK, Sharma KN. Dynamics of forms of inorganic phosphorus during wheat growth in a continuous maize-wheat cropping system. *Journal of the Indian Society of Soil Science*. 2007;55:139-46.
54. Laxminarayana K. Effect of P solubilizing microorganisms on yield of rice and nutrient availability in an acid soil of Mizoram. *Journal of the Indian Society of Soil Science*. 2005;53(2):240-43.
55. Elkoca E, Kantar F, Sahin F. Influence of nitrogen fixing and phosphorus solubilizing bacteria on the nodulation, plant growth, and yield of chickpea. *Journal of Plant Nutrition*. 2007;31(1):157-71. <https://doi.org/10.1080/01904160701742097>