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Native soil phosphorous solubilization and enhancement of nutrient use efficiency by using bio fertilizers in core rainfed groundnut growing alfisols

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Abstract

Sustainable intensification of rainfed groundnut (*Arachis hypogaea* L.) grown on Alfisols, where low available P and fluctuating rainfall limit productivity, depends on better nutrient-use efficiency (NUE) and efficient use of native soil phosphorus (P). This study evaluated strategies to mobilize native soil P and enhance P-use efficiency under core rainfed groundnut production on Alfisols. A field experiment was conducted using a randomized complete block design with three replicates to evaluate the effects of reduced fertilizer (HRDF) and soil test-based fertilizer (STBF), applied alone or in combination with biofertilizers (PSB, PSF, and AM fungi). Observations on PH, EC, organic carbon, available N, available P, available K, available sulfur, copper, iron, zinc, plant population, plant height, no. of branches/plant, root length, number of root nodules, no. of pods/sq.mt, pod yield, haulm yield, test weight, and shelling percentage were measured. When compared to chemical fertilizer alone, the results demonstrated that treatments receiving integrated microbial consortia greatly enhanced pod formation, nutrient uptake, and soil fertility. Treatments combining PSB + PSF + AM fungus (T₅ and T₉) showed the maximum number of pods per square meter (255.09), pod yield (1024.88 kg ha⁻¹) and root nodulation (68 nodules plant⁻¹). Because of greater biological activity and better P mobilization, inoculated plots also had higher levels of soil accessible N, P and K as well as micronutrients like copper, iron, zinc and manganese. Overall, under rainfed Alfisol conditions, the integrated use of PSB, PSF, AM fungi, and FYM significantly increased the mobilization of native soil phosphorus, improved nutrient-use efficiency, and raised groundnut yield.

Keywords: Groundnut, Alfisol, phosphorus solubilization, phosphate-solubilizing bacteria, nutrient-use efficiency, rainfed agriculture, integrated nutrient management

Introduction

Groundnut (*Arachis hypogaea* L.) is a major rainfed legume crop cultivated extensively in semi-arid regions, including the Alfisol tracts of southern India. Due to strong fixation by iron and aluminum oxides, poor organic content, and coarse texture that limits nutrient retention, alfisols usually have low to moderate plant-available phosphorus (P) (Sanyal & De Datta, 1991; Kamprath, 1984)^[10, 5]. Although phosphorus is necessary for groundnut root growth, nodulation, nitrogen fixation, pod formation, and successful reproduction, P deficiency continues to be a significant yield-limiting factor in dryland settings (Rego *et al.*, 2007)^[8]. Due to unpredictable rainfall and decreased nutrient absorption in dry soils, the problem of low P availability is made worse under rainfed circumstances (Venkateswarlu & Shanker, 2009)^[15]. Furthermore, smallholder farmers are constrained by high fertilizer costs and restricted access to chemical fertilizers, which makes native soil P mobilization options more important and financially feasible (Subba Rao *et al.*, 2015)^[13].

The ability of microbial inoculants like phosphate-solubilizing bacteria (PSB), phosphate-solubilizing fungi (PSF), and arbuscular mycorrhizal (AM) fungi to solubilize sparingly soluble soil P through mechanisms like organic acid secretion, phosphatase release, chelation and increased rhizosphere activity is well known (Rodríguez & Fraga, 1999; Sharma *et al.*, 2013)^[9, 11]. By creating vast hyphal networks that expand the root absorptive surface, AM fungi also enhance the uptake of P and micronutrients (Smith & Read, 2008)^[12]. It has been demonstrated

that combining microbial inoculants with organic additions like farmyard manure (FYM) improves nutrient-use efficiency (NUE) in dryland agriculture, promotes nutrient cycling, and creates a beneficial soil biological environment (Bolan *et al.*, 1990; Reddy *et al.*, 2016)^[2, 7]. Particularly in nutrient-deficient Alfisols, such integrated nutrient management techniques improve soil health and crop output while reducing reliance on chemical fertilizers (Vassilev & Vassileva, 2003)^[14].

In light of this, the current study was carried out to characterize native phosphorus fractions in Alfisols that grow groundnuts, analyze the impacts of microbial P-mobilizing inputs on soil phosphatase activities, and evaluate their effects on groundnut development and pod yield under rainfed conditions.

Materials and Methods

Site description

The experiment was conducted at the ANGRAU, Agricultural Research Station, Anantapur, which is situated in a core rainfed groundnut growing Alfisol zone (latitude, 14° 41' 218" N, longitude, 77° 40' 115" E), from kharif 2013 to kharif 2016. With 36 wet days and an average annual rainfall of 590 mm, the location has a semi-arid climate. Red sandy-loam Alfisol with pH 6.2, organic carbon 0.48%, and accessible phosphorus (Olsen P) of 6.5 mg kg⁻¹ (poor) was found in the pre-sowing soil analysis (0-15 cm).

Experimental design and treatments

The experiment was set up on a 5 m × 5 m area in a randomized complete block design with three replications. T₁ (control); T₂ (half recommended fertilizer dose, HRDF: 10:20:20 kg NPK/ha); T₃ (HRDF + PSB + AM fungi); T₄ (HRDF + PSF + AM fungi); T₅ (HRDF + PSB + PSF + AM fungi); T₆ (STBF, soil test-based fertilizer); T₇ (STBF + PSB + AM fungi); T₈ (STBF + PSF + AM fungi); T₉ (STBF + PSB + AM fungi only). PSB (*Bacillus megatherium* var. *phosphaticum*) at 5 kg/ha, PSF (*Aspergillus awamori*) at 5 kg/ha, and AM fungi (arbuscular mycorrhiza) at 12.5 kg/ha were the microbial inoculants. A beginning dosage of farmyard manure (FYM) was administered at 500 kg/ha.

Seeds of groundnut K6 variety were sown at recommended spacing. Standard agronomic methods for controlling weeds, pests, and diseases were consistently applied in accordance with ANGRAU recommendations. The PSB consortium included well-characterized strains, such as *Bacillus megatherium* var. *phosphaticum*, that are known to produce organic acids and phosphatases and to solubilize phosphate. The soil application techniques adhered to known protocols, and the inoculum amount was around 10⁸ CFU g⁻¹ seed. Rock phosphate (RP) was obtained locally; FYM was well-decomposed; PSF (*Aspergillus awamori*) enhanced soil P mobilization; and AM fungus (*Arbuscular mycorrhiza*) transported P into roots.

Measurements and sampling

Soil analyses involved baseline and post-harvest sampling from 0-15 cm depth to determine pH, organic carbon, available P (Olsen method), and available N and K. Plant growth and yield parameters measured included plant height (cm), number of branches per plant, number of pods per sq. m, pod yield (kg ha⁻¹), and haulm yield (kg ha⁻¹). Agronomic efficiency of P was calculated as (yield in treated plot – yield in control) / P applied (kg seed yield per kg P applied). All samples were analyzed following standard protocols (e.g., Jackson 1973; Olsen *et al.* 1954). Data underwent ANOVA, with means compared using LSD at P = 0.05; correlation and regression analyses explored relationships among soil P fractions and yield parameters.

Results

Plant Growth Parameters

Plant height, number of branches, root characteristics and pod-bearing capacity varied significantly between treatments. Microbial inoculation treatments (T₃-T₁₀) showed a modest improvement over control (T₁), with plant heights ranging from 22.40 cm (T₅) to 24.11 cm (T₁₀). T₈ (STBF + PSF + AM fungus) had the most branches per plant (4.52), followed by T₇ (4.30), demonstrating the beneficial effects of combined organic and microbial nutrition management. Strong responses to biological inoculants was demonstrated by root nodulation; T₉ (STBF + PSB + PSF + AM fungus) recorded the highest number of nodules (68 nodules/plant), about twice as many as the control (36.87). With very slight increases in infected treatments, root length remained within the 7.54-8.78 cm range.

Table 1: Effect of P-mobilizing inputs on growth parameters of groundnut in Alfisols (Kharif, 2013 to Kharif, 2016)

Treatments	Plant height (cm)	No. of branches/plant	No. of pods/sq.mt	Root length (cm)	No. of Root nodules
T ₁	22.53	3.87	183.10	8.46	36.87
T ₂	23.42	4.01	219.85	8.32	27.53
T ₃	23.66	4.07	229.86	8.75	22.63
T ₄	23.24	4.17	221.16	7.79	29.57
T ₅	22.40	4.06	255.09	8.78	31.27
T ₆	22.42	4.01	234.28	8.55	37.63
T ₇	22.56	4.30	226.80	7.54	34.73
T ₈	23.48	4.52	223.75	8.55	35.63
T ₉	23.70	3.97	241.66	7.73	68.00
T ₁₀	24.11	3.82	227.60	7.71	35.27
C.D	6.448	N/A	153.08	N/A	38.136
SE (m) ±	2.153	0.198	51.129	0.421	11.755
SE (d)	3.045	0.279	72.307	0.595	16.624
C.V.(%)	16.199	8.393	33.730	7.243	46.288

Yield Attributes and Yield

The number of pods per square meter showed clear treatment effects, ranging from 183.10 pods/m² in T₁ (control) to a maximum of 255.09 pods/m² in T₅ (HRDF + PSB + PSF + AM fungi). Treatments T₉ (241.66 pods/m²) and T₆ (234.28 pods/m²) also performed strongly, indicating considerable improvement with integrated nutrient management and microbial inoculation. Intermediate pod numbers were recorded in T₃ (229.86 pods/m²), T₇ (226.80 pods/m²), T₁₀ (227.60 pods/m²), and T₈ (223.75 pods/m²). Treatment T₂ (219.85 pods/m²) showed an improvement over control but was inferior to treatments receiving microbial consortia.

The trend in pod numbers closely aligned with pod yield performance, with the highest pod yields recorded in T₉ (1024.88 kg ha⁻¹) and T₅ (995.25 kg ha⁻¹)—the treatments that also had the highest pod numbers. Pod production was significantly increased by integrated P-mobilizing treatments. T₉ demonstrated the clear benefits of combining PSB + PSF + AM fungal with STBF by producing the most pods (1024.88 kg ha⁻¹), followed by T₅ (995.25 kg ha⁻¹) and T₈ (974.42 kg ha⁻¹). These treatments outperformed chemical fertilizer alone (T₂: 866.33 kg ha⁻¹) and the control (T₁: 726.34 kg ha⁻¹). Furthermore, haulm yield increased with the highest values recorded for T₅ (2014.56 kg ha⁻¹) and T₉ (2012.89 kg ha⁻¹), indicating balanced biomass accumulation and plant growth under integrated nutrition management. The percentage of shelling peaked in T₇ and remained rather stable among treatments (67-70.46%) (Table 1).

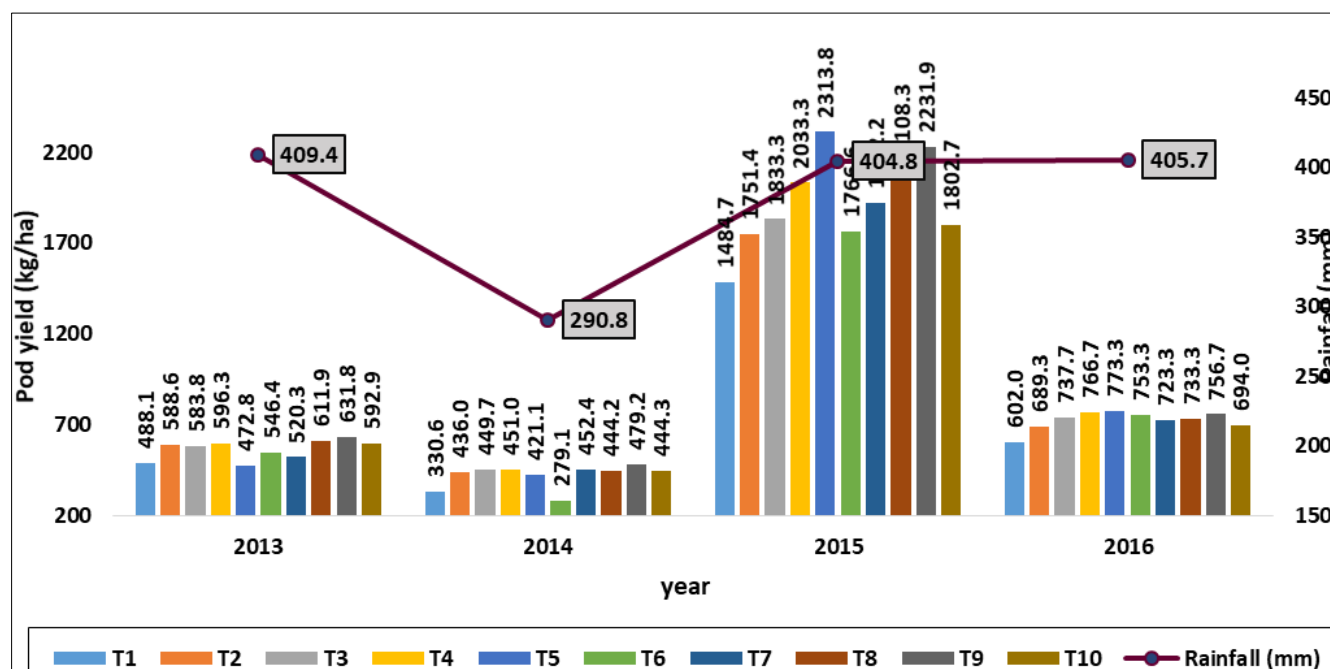


Fig 1: Effect of rainfall on pod yield in groundnut with different treatments

The highest yields were recorded in 2015 under 404.8 mm of rainfall, indicating ideal moisture conditions for better groundnut pod yield (Fig 1). Yield varied significantly between years and treatments. Moisture stress has a negative impact on pod yield, as seen by the lowest yields in 2014, which had the least rainfall

(290.8 mm). Despite comparable rainfall amounts, moderate yields were seen in 2013 and 2016, indicating that variables like rainfall distribution may potentially affect productivity. Overall, rainfall and pod yield were positively correlated, and treatments T₈ and T₉ continuously performed better over time.

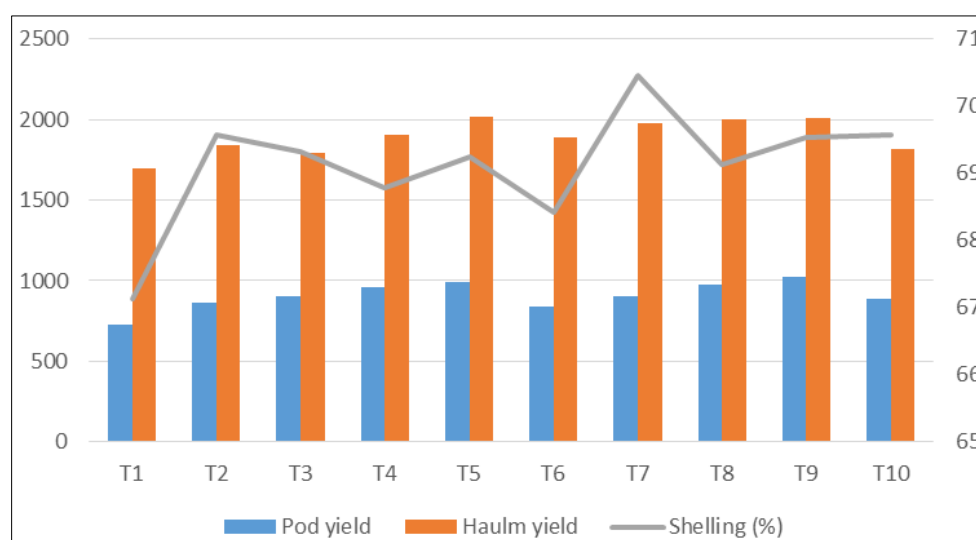


Fig 2: Effect of P-mobilizing inputs on yield parameters of groundnut in Alfisols (Kharif, 2013 to Kharif, 2016)

Soil Chemical Properties

The highest values of soil organic carbon were found in T₅ (0.54%), T₂, T₈, T₉ (0.50%), and T₁₀ (0.47%), as opposed to 0.46% in the control, indicating modest gains under microbial and STBF-based treatments. Under microbial treatments, available nitrogen improved from 149 kg ha⁻¹ (T₁) to 179.25 kg ha⁻¹ in T₉, indicating enhanced root symbiosis and greater mineralization.

Because of fertilizer application, available phosphorus levels increased significantly in treatments receiving PSB/PSF/AM fungus. T₂ had the highest values (80 kg ha⁻¹), followed by T₁₀ (68 kg ha⁻¹) and T₄ (68.25 kg ha⁻¹). Under microbial inoculation, the availability of potassium was maximum in T₂ (419.5 kg ha⁻¹) and T₄ (421 kg ha⁻¹), while the availability of sulfur and micronutrients improved moderately.

Table 2: Effect of P-mobilizing inputs on soil chemical properties and micronutrient availability at harvest (Kharif, 2013 to Kharif, 2016)

Treatments	PH	EC	Organic 'C'	Available 'N' kg/ha	Available 'P' kg/ha	Available 'K' kg/ha
T ₁	5.95	0.09	0.46	149	51.5	310
T ₂	5.97	0.10	0.50	175	80.0	419.5
T ₃	5.83	0.09	0.46	168.75	63.25	374
T ₄	5.83	0.09	0.47	176.5	68.25	421
T ₅	5.75	0.12	0.54	178.25	67.5	385.75
T ₆	5.58	0.11	0.47	174.75	61.75	361.5
T ₇	5.43	0.14	0.48	176.75	61.75	376.75
T ₈	5.58	0.10	0.50	177.75	56.0	389
T ₉	5.59	0.12	0.50	179.25	55.5	406.5
T ₁₀	5.71	0.13	0.47	172.25	68.0	394
C.D	0.16	0.088	0.14	21.065	13.689	103.160
SE (m)	0.20	0.029	0.04	7.035	4.527	34.454
SE (d)	0.29	0.041	0.06	9.949	6.466	48.725
C.V(%)	6.66	45.88	16.92	7.369	14.494	18.639

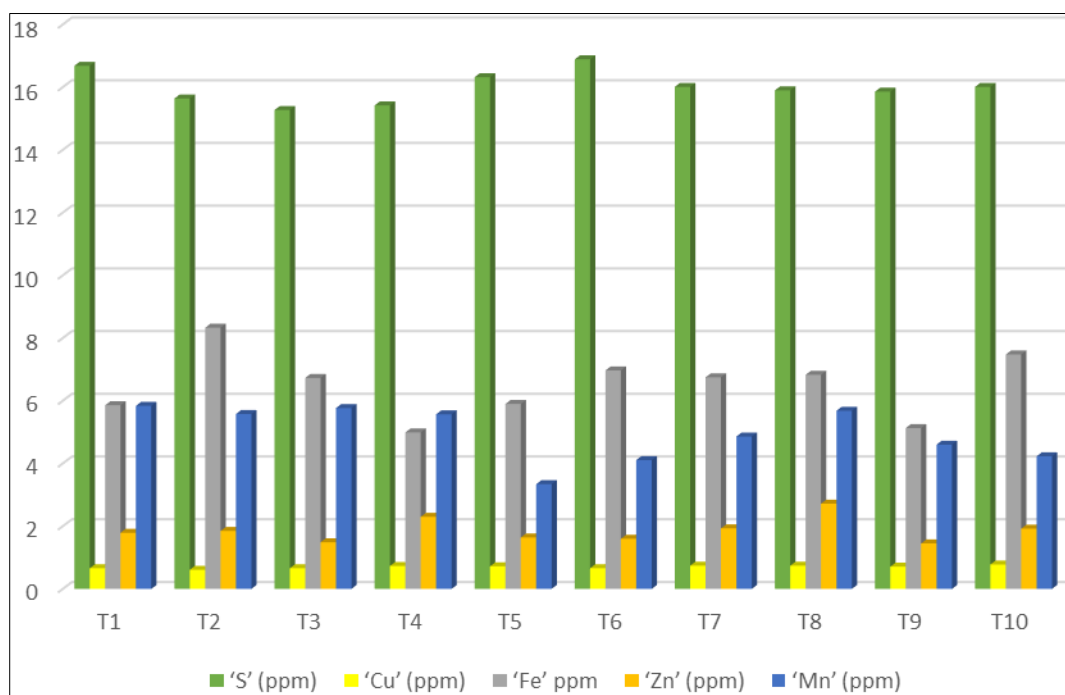
Micronutrient Availability (Cu, Fe, Zn, Mn)

Significant differences were observed among the treatments for micronutrient availability in soil at harvest.

Copper (Cu)

The copper level of the soil varied from 0.61 to 0.78 ppm, with T₂ having the lowest value (0.61 ppm) and T₁₀ having the highest

(0.78 ppm). In contrast to the control (0.66 ppm), treatments with microbial inoculants, specifically AM fungus and PSF, such as T₇ (0.74 ppm) and T₈ (0.74 ppm), demonstrated enhanced Cu availability. Cu solubility was probably improved by increased root exudation and organic acid generation during microbial activity.

**Fig 3:** Effect of P-mobilizing inputs on micronutrient availability at harvest (Kharif, 2013 to Kharif, 2016)**Iron (Fe)**

Available iron showed notable variation, ranging from 4.99 ppm in T₄ to 8.33 ppm in T₂, which recorded the highest Fe content. Microbial treatments such as T₁₀ (7.48 ppm) and T₈ (6.83 ppm) also enhanced Fe availability, likely due to chelation and rhizosphere acidification processes. The control recorded 5.86 ppm, which was lower than most inoculated treatments.

Zinc (Zn)

The lowest Zn availability was observed in T₉ (1.45 ppm) and T₃ (1.49 ppm), while the highest was recorded in T₈ (2.72 ppm). AM fungi in T₈ may have contributed to improved Zn uptake and mobility through enhanced root surface area. The control (1.79 ppm) was intermediate, indicating that specific microbial

combinations (especially AMF + PSF) were more beneficial for Zn solubilization (Table 2).

Discussion

This study demonstrated the importance of microbial P-solubilization and integrated nutrient management in enhancing native soil P availability and improving groundnut productivity in rainfed Alfisol systems. The combined application of PSB, PSF, and AM fungi—particularly when integrated with STBF and FYM—significantly enhanced plant growth, nutrient uptake, and pod yield.

Effect of Bio-inoculants on Growth and Nodulation

The pronounced increase in root nodulation, especially in T₉,

indicates effective colonization by PSB, PSF, and AM fungi and improved rhizosphere biological activity. AM fungi enhance P uptake through extraradical hyphae, while PSB and PSF release organic acids and phosphatases that mobilize sparingly soluble P pools. Enhanced nodulation further improves N fixation, reflected in higher available N levels in biologically treated plots.

Yield improvement through enhanced P Mobilization

The significant increases in pod and haulm yield under combined microbial treatments corroborate earlier findings that P-solubilizing inoculants improve nutrient-use efficiency and yield under low-P conditions typical of Alfisols. Treatments T₅ and T₉, receiving the full microbial combination (PSB + PSF + AM fungi), consistently outperformed the chemical fertilizer treatments (T₂), emphasizing the capacity of biological agents to mobilize native soil P and improve physiological efficiency. The improvement in pod number and seed filling may be attributed to improved energy metabolism, better root architecture, and balanced nutrient supply, especially during pegging and pod development stages.

Soil Fertility Enhancement

The role of organic acids, enzymatic activity, and improved nutrient cycling is confirmed by the rise in accessible N, P, and K under microbial treatments. Increased organic carbon in T₅ indicates that microbial biomass and FYM breakdown have cumulative benefits. Additionally, PSB/PSF's chelation and organic acid release enhanced micronutrient availability.

The moderate acidification brought on by microbial secretions is reflected in lower soil pH in some treatments (e.g., T₇: pH 5.43), which is advantageous in Alfisols for mobilizing P that would otherwise be fixed by Fe and Al oxides.

The results of this study unequivocally show that, in rainfed Alfisol conditions, the combined application of PSB, PSF, and AM fungus greatly enhances native soil phosphorus mobilization, nutrient uptake, and groundnut pod yield. Through mechanisms like organic acid secretion, phosphatase synthesis, and chelation of Fe/Al-bound phosphates—processes that have been thoroughly described by Rodríguez and Fraga (1999)^[9] and Sharma *et al.* (2013)^[11]—microbial inoculants are known to increase P availability. The significant rise in root nodulation observed in treatments T₅ and T₉ is consistent with previous findings that PSB and AM fungi work in concert to improve rhizobial colonization, nutrient absorption, and root activity (Gyaneshwar *et al.*, 2002)^[4].

The higher pod number and yield in T₅ and T₉ can be attributed to improved P uptake, as phosphorus is essential for peg formation, pod setting, and energy metabolism in legumes. Similar enhancements in pod yield with microbial consortia were reported in groundnut by Reddy *et al.* (2016)^[7] and Aher *et al.* (2015)^[1]. The integration of FYM further supported microbial activity and nutrient mineralization, consistent with findings by Bolan *et al.* (1990)^[2] on organic matter improving microbial-mediated P cycling.

Micronutrient enhancement (Cu, Fe, Zn) under microbial treatments may be linked to organic acid-mediated solubilization and AM fungal facilitation of micronutrient uptake. This is supported by the work of Smith & Read (2008)^[12], who documented that AM fungi improve Zn and Cu acquisition through expanded hyphal networks. Increased Fe availability in treated plots is consistent with chelating effects of fungal metabolites, as observed by Kucey (1988)^[6].

The results confirm that chemical P alone (T₂) is insufficient in Alfisols due to strong fixation by Fe/Al oxides, a phenomenon

previously described by Sanyal and De Datta (1991)^[10]. In contrast, microbial consortia effectively overcame P-fixation barriers and promoted higher nutrient-use efficiency. Such biological approaches are recognized as sustainable alternatives for P management in dryland systems, as also emphasized by Vassilev & Vassileva (2003)^[14].

Overall, the study supports a growing body of evidence that microbial consortia + FYM represent a viable, eco-friendly strategy for improving P availability, soil health, and productivity in rainfed groundnut-based farming systems.

Implications for Rainfed Alfisols

Given the inherently low P supply in Alfisols and the high cost of chemical fertilizers for rainfed farmers, the results highlight a sustainable pathway for improving groundnut productivity. Microbial consortia reduce dependency on external P fertilizers, improve soil health, and allow for stable yields even under moisture-stress conditions typical of rainfed regions.

Conclusion

The research showed that the utilization of phosphate-solubilizing bacteria (PSB), phosphate-solubilizing fungi (PSF), and arbuscular mycorrhizal (AM) fungi in conjunction with organic inputs greatly enhanced the nutrient availability, plant growth, and productivity of groundnuts cultivated in rainfed Alfisol conditions by mobilizing native soil phosphorus. With the highest pod numbers per square meter, maximum pod yield, enhanced root nodulation, and improved soil nutritional status, treatments T₅ (HRDF + PSB + PSF + AM fungi) and T₉ (STBF + PSB + PSF + AM fungi) continuously outperformed the others. The availability of vital micronutrients like copper, iron, zinc, and manganese was also improved by these treatments, suggesting improved nutrient cycling and heightened microbial activity in the rhizosphere. The findings unequivocally show that microbial consortia are essential for releasing fixed phosphorus, enhancing the effectiveness of nutrient usage, and maintaining production in conditions of moisture stress that are common in rainfed systems. For smallholder farmers in Alfisol regions, integrated nutrient management techniques utilizing PSB, PSF, AM fungus, and FYM present a viable, affordable, and environmentally responsible substitute for chemical fertilizers. Adopting such biological nutrient mobilization techniques can improve the resilience of rainfed agriculture and increase the sustainability of groundnut output.

Conflict of Interest: The authors declare that they have no competing interests.

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