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Microbial Regulation of Available Nitrogen and Potassium in Groundnut (*Arachis hypogaea* L.)

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Groundnut is a strategic oilseed legume for India because it contributes edible oil, plant protein and biological nitrogen inputs to rainfed farming systems. Recent national estimates report record Indian groundnut production of 118.96 lakh tonnes in 2024-25, within a total oilseed production estimate of 426.09 lakh tonnes. Despite this progress, productivity remains strongly constrained by uneven soil moisture, low nutrient-use efficiency, phosphorus fixation, micronutrient limitations, and weak biological functioning in degraded soils. This article synthesizes the agronomic role of phosphate-solubilizing bacteria (PSB) and vesicular-arbuscular mycorrhiza, now commonly termed arbuscular mycorrhizal fungi (VAM/AMF), with special focus on available nitrogen (N) and potassium (K) dynamics in groundnut. PSB primarily improves phosphorus availability, which indirectly supports root growth, nodulation and biological N fixation. VAM improves root-soil contact through external hyphae, enhances uptake of relatively immobile nutrients, supports water relations and can indirectly improve K cycling through better biomass production and rhizosphere activity. The expected soil pattern is that available N before harvest is stable or slightly increased where nodulation is improved, while available K may decline before harvest due to stronger crop uptake and then recover after harvest through residue decomposition and microbial mobilization. The paper provides a publishable article structure, evidence-based interpretation tables, an India-specific context, and a field-experiment framework for validating PSB-VAM effects without fabricating unverified experimental results.

Keywords: groundnut, PSB, VAM, arbuscular mycorrhiza, available nitrogen, available potassium, biological nitrogen fixation, oilseeds.

Introduction

Groundnut (*Arachis hypogaea* L.) is both an oilseed and a food-legume crop, making its nutrient economy different from non-leguminous oilseeds. The crop removes considerable quantities of nitrogen, phosphorus, potassium, calcium and sulphur, yet it also contributes nitrogen to the soil-plant system through symbiosis with Bradyrhizobium/Rhizobium-like nodule bacteria. For sustainable intensification, the major agronomic question is therefore not only how much fertilizer is applied, but how efficiently soil biology can convert fixed, insoluble or weakly accessible nutrients into plant-available pools. India's 2024-25 agricultural estimates show why groundnut deserves renewed agronomic attention. The Ministry of Agriculture and Farmers' Welfare reported total oilseed production of 426.09 lakh tonnes and groundnut production of 118.96 lakh tonnes, both indicating the importance of oilseed systems for edible-oil security. APEDA also identifies India as the second-largest global producer of groundnuts and lists Gujarat, Rajasthan, Madhya Pradesh, Tamil Nadu, Karnataka, Uttar Pradesh, Andhra Pradesh, Maharashtra, West Bengal and Telangana among major producing states. These figures underline the need for nutrient-management approaches suitable for rainfed, semi-arid and resource-limited farms. Biofertilizers are not substitutes for all nutrient inputs; they are biological efficiency tools. Their value is greatest when they are used with balanced fertilization, seed quality, moisture conservation and correct inoculation practices. In groundnut, PSB and VAM are particularly relevant because phosphorus availability controls root growth and energy supply for nodulation, while VAM improves root exploration, nutrient acquisition and stress tolerance.

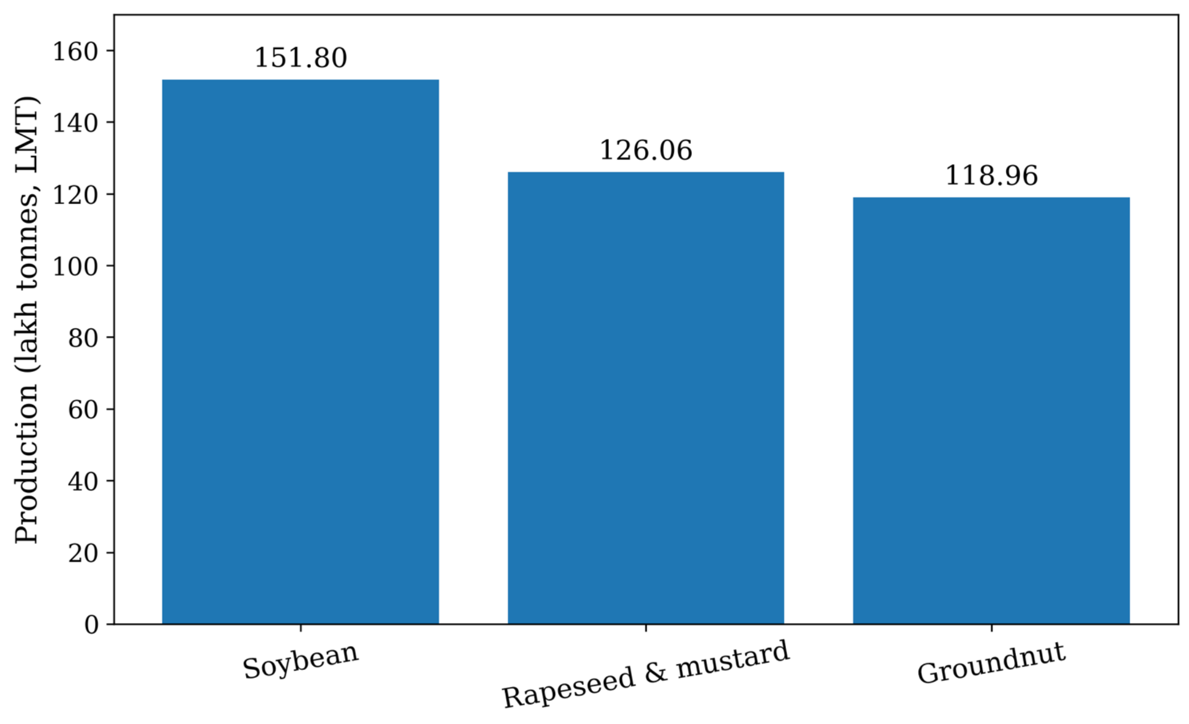

Fig. 1. Major Indian oilseed production estimates in 2024-25. Source data: Ministry of Agriculture & Farmers' Welfare, Third Advance Estimates, 28 May 2025.

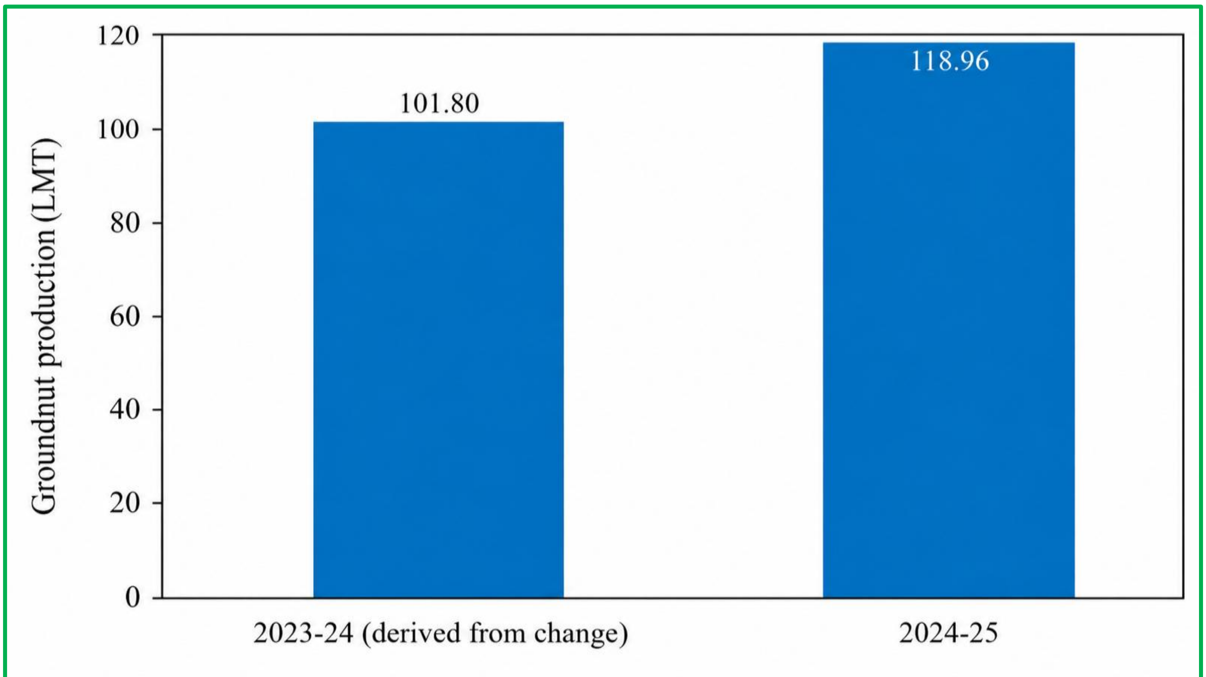

Fig. 2. Groundnut production increase from 2023-24 to 2024-25 based on the reported increase of 17.16 LMT. Source data: Ministry of Agriculture & Farmers' Welfare, Third Advance Estimates.

Objective and scope of the article

To explain the effect of PSB and VAM on available N and K in groundnut at pre-harvest and post-harvest stages.

To distinguish direct microbial effects from indirect crop-growth and residue-cycling effects.

To provide an India-specific, publishable interpretation using verified production statistics and peer-reviewed agronomic evidence.

To propose a field-validation framework that can be used by researchers without presenting invented experimental data as real results.

Scientific basis: PSB and VAM functions in groundnut rhizosphere

Phosphate-solubilizing bacteria

Phosphate-solubilizing bacteria convert sparingly soluble phosphate fractions into plant-available orthophosphate through mechanisms such as organic-acid production, chelation, proton release, phosphatase activity and rhizosphere pH modification. In groundnut, this is important because root development, flowering, pegging and pod filling are sensitive to P supply. Phosphorus is also central to ATP generation; therefore, improved P availability indirectly supports the energy-intensive process of biological nitrogen fixation. The effect of PSB on available N is therefore mostly indirect. PSB does not fix N in the same way as rhizobia, but it improves P nutrition, root growth and nodule functioning. Where the crop is able to form effective nodules, this can result in more N fixed during the season and more residual N returned through roots, nodules and haulm residues.

Vesicular-arbuscular mycorrhiza / arbuscular mycorrhizal fungi

VAM/AMF colonize the root cortex and produce external hyphae that extend beyond the root depletion zone. This increases the functional absorbing area of the root system. Although AMF are best known for improving P uptake, recent evidence also supports their role in K uptake, water transport, stress physiology and nutrient-transporter regulation. These functions are especially valuable in rainfed groundnut because moisture stress reduces mass flow and diffusion of nutrients. VAM can influence soil available N through better plant vigour, improved nodulation environment, uptake of micronutrients required for nitrogenase activity, and increased below-ground biomass. VAM may also influence available K through greater soil-volume exploration, mobilization of exchangeable and non-exchangeable K pools, and faster recycling from residues after crop maturity.

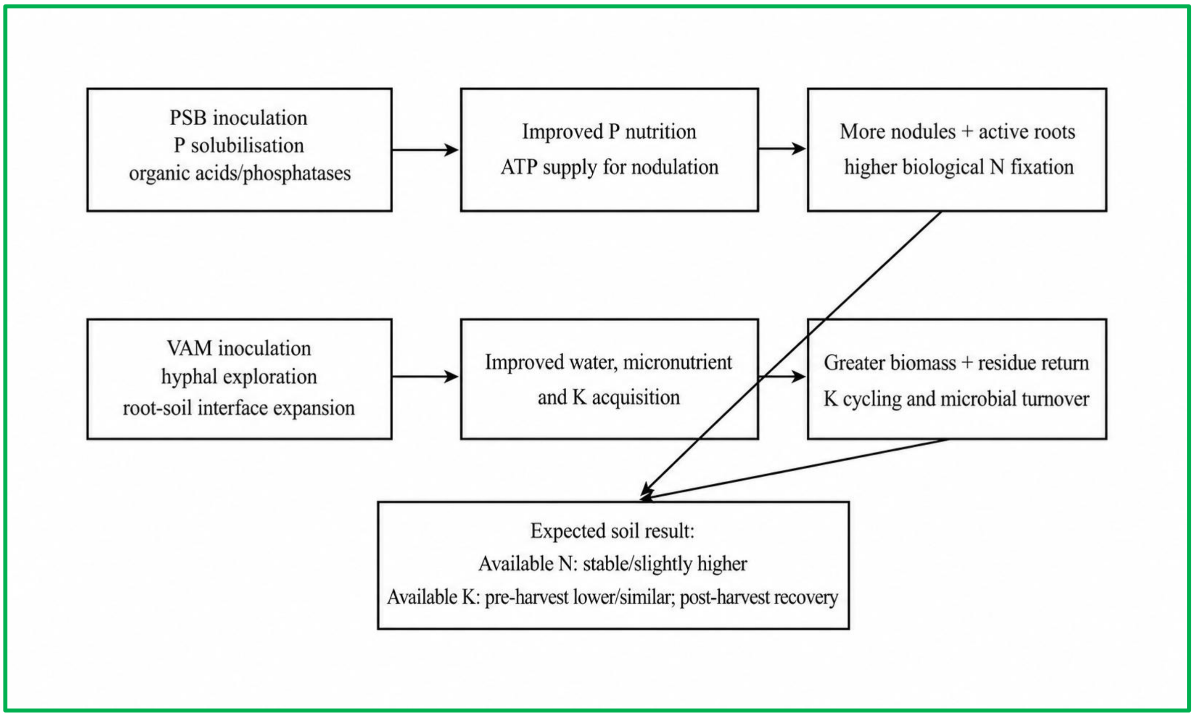

Fig. 3. Conceptual mechanism linking PSB and VAM to available N and K dynamics in groundnut.

Expected effect on available nitrogen

Pre-harvest stage

At pre-harvest, available soil N under PSB and VAM is expected to remain stable or show a slight increase over uninoculated control, provided nodulation is effective and soil moisture is not severely limiting. The explanation is biological rather than purely chemical. Better P supply from PSB improves root growth and ATP availability, while VAM improves nutrient uptake and root-soil contact. Together these effects support more nodules, higher nodule activity and stronger biological N fixation. In a legume such as groundnut, the observed available N at any sampling date is the net result of four simultaneous processes: mineral N uptake by the crop, biological N fixation, N mineralization from organic matter, and immobilization by microbes. Therefore, available N may not always rise sharply during active crop growth because a healthy crop also removes N rapidly. A stable value can still indicate improvement if biomass and pod yield are higher.

Post-harvest stage

After harvest, available N may be equal to or slightly higher than control because roots, nodules, fallen leaves and fine residues decompose and return organic N to the soil. VAM-treated plots often have more root biomass and a larger biologically active rhizosphere, which can improve N mineralization during the post-harvest period. However, the size of the increase depends on residue retention, soil moisture, temperature, organic carbon and the amount of N removed in pods and haulm.

Why VAM can be higher than PSB for available N

VAM can show higher available N than PSB because it acts at the root-system scale. The external hyphal network increases nutrient and water access, supports plant health under stress and improves the physical connection between plant roots and soil microsites. Better plant growth may improve nodulation and biological N fixation, while greater root residue can contribute to residual N after harvest. PSB remains important, especially where P fixation is severe, but its effect on N is more dependent on P limitation and the presence of effective rhizobia.

Expected effect on available potassium

Pre-harvest stage

Available K commonly shows a slight decrease or remains similar to control before harvest. This pattern is agronomically logical. PSB and VAM treatments can improve plant growth, leaf area, root length and pod development; the improved crop then absorbs more K. Since K is required for enzyme activation, stomatal regulation, assimilate transport, oil formation and stress tolerance, a vigorous groundnut crop can deplete the immediately available K pool even when total K reserves remain high.

Post-harvest stage

After harvest, available K can recover to control level or increase slightly because K is relatively mobile in plant residues and is released rapidly during decomposition. Unlike N, K is not built into proteins or nucleic acids; much of it remains in ionic form in plant tissues. Therefore, residue return, microbial turnover and wetting-drying cycles can release K back into exchangeable and solution pools. This is why post-harvest soil K may not remain depressed even after strong crop uptake.

Why VAM can be higher than PSB for available K

VAM can show a stronger effect on K than PSB because its hyphae explore soil volumes that roots alone cannot reach. This is important in dry or compacted soil, where diffusion of K towards the root surface is restricted. VAM also improves water relations, and water status controls K movement to roots. The post-harvest advantage of VAM may also arise indirectly from greater biomass production and residue return, which accelerates K cycling.

Table 1. Evidence-based interpretation of PSB and VAM effects on soil parameters.

Soil parameter/stage	Expected PSB effect	Expected VAM effect	Main interpretation
Available N: pre-harvest	Stable or slight increase	Slight to moderate increase	Improved P nutrition, root growth, nodulation and biological N fixation
Available N: post-harvest	Equal or slightly higher than control	Often higher than PSB when root biomass and nodulation are strong	Residual roots, nodules and microbial turnover release N
Available K: pre-harvest	Similar or slight decrease	Similar or slight decrease despite better uptake	Better crop growth increases K removal from available pool
Available K: post-harvest	Recovery or slight increase	Recovery often stronger than PSB	Residue decomposition, hyphal exploration and microbial cycling
Overall comparison	Useful where P fixation restricts groundnut growth	Usually stronger broad rhizosphere effect	VAM improves soil-volume exploration; PSB mainly improves P solubilization

India-specific relevance

Indian groundnut cultivation spans diverse ecologies, from Gujarat's large commercial belt to semi-arid Rajasthan, black and red soils of central and southern India, and emerging summer groundnut areas in Uttar Pradesh. Many of these regions face moisture stress, low organic carbon, variable P fixation and weak biological activity. Under such conditions, microbial inoculants can be useful only when agronomic management supports survival and root colonization. The most practical implication is that VAM and PSB should be viewed as components of integrated nutrient management rather than stand-alone inputs. In rainfed groundnut, the probability of response is higher when seed treatment or soil application is combined with adequate organic matter, gypsum or calcium management where required, balanced P and K fertilization, good seed quality, and timely sowing with moisture conservation.

Proposed field methodology for publishable validation

A rigorous experiment should be conducted for at least two seasons because microbial responses are strongly modified by rainfall, soil moisture and soil temperature. A randomized block design or factorial randomized block design is suitable.

Component	Recommended protocol
Design	Factorial randomized block design with three replications
Treatments	Control, PSB, VAM, PSB+VAM, recommended fertilizer dose, 75% recommended fertilizer dose + PSB+VAM
Crop	Groundnut variety adapted to the region; seed inoculated according to local recommendations
Soil sampling	Initial, 45 DAS, pre-harvest and post-harvest samples from 0-15 cm depth
Measurements	Available N, available K, available P, organic carbon, microbial biomass C, nodule number, nodule dry weight, root length density, pod yield, haulm yield, oil content
Statistics	ANOVA, standard error of mean, critical difference/LSD at 5%, correlation and principal component analysis if assumptions are met
Quality control	Report soil type, rainfall, inoculant source, viable cell/spore count, method of application and residue handling

Data-analysis model

For a balanced randomized block experiment, the basic model may be written as: Yij = μ + Ti + Bj + eij, where Yij is the observed soil or crop parameter, μ is the overall mean, Ti is the treatment effect, Bj is the block effect and eij is the random error. For a factorial design, interaction terms should be added to test whether PSB and VAM act additively or synergistically. The analysis must check normality and homogeneity of variance before final interpretation. The most important statistical caution is that soil available N and K should not be interpreted alone. A treatment can reduce available K at pre-harvest and still be agronomically superior if plant uptake, yield and post-harvest recovery are higher. Therefore, available nutrient data must be discussed together with nutrient uptake, biomass and yield.

Discussion

The central agronomic interpretation is that PSB and VAM modify nutrient availability through different biological pathways. PSB increases the availability of P that would otherwise remain fixed in soil minerals. This effect can improve nodulation and N fixation in legumes. VAM broadens the effective root system and improves access to water and relatively immobile nutrients. Thus, VAM can have a wider effect on root physiology, nutrient uptake and residue-mediated cycling. For available N, VAM may outperform PSB because the fungus indirectly supports nodulation and root functioning. However, the strongest N effect will usually occur when rhizobial symbiosis is effective. If native rhizobia are weak or soil pH, drought or micronutrient deficiency limits nodulation, VAM alone cannot fully correct N fixation. This is why integrated inoculation with Rhizobium, PSB and VAM may be superior to any single inoculant in some environments. For available K, the interpretation is more subtle. Higher plant growth often reduces the soil-test K value during the crop period because the crop is taking up more K. This should not be mistaken as negative microbial performance. Post-harvest recovery of K is a better indicator of nutrient cycling, especially where residues are retained. VAM can support this recovery by increasing biomass and by improving access to K-bearing microsites in soil. The article also highlights a publication-quality requirement: researchers should avoid presenting direction-only statements as universal truths. Microbial effects depend on soil texture, pH, organic carbon, indigenous microbial population, inoculant viability, rainfall, fertilizer background and crop variety. Therefore, statements such as 'VAM is always higher than PSB' should be written more precisely as 'VAM is generally expected to show a stronger broad rhizosphere effect, especially where root exploration and moisture stress are major constraints'.

Practical recommendations for farmers and researchers

- Use fresh, quality-certified inoculants and avoid exposing them to direct sunlight, high temperature or fungicide incompatibility.
- Apply PSB primarily to improve P availability and support early root development and nodulation.
- Apply VAM where soil biological activity is weak, P and K diffusion is restricted, or moisture stress limits nutrient uptake.
- Do not judge K response only from pre-harvest soil K; include crop uptake and post-harvest soil K.
- Retain or recycle groundnut residues where possible because residue return is important for post-harvest K recovery and N cycling.
- Use balanced fertilization; microbial inoculants improve nutrient-use efficiency but do not replace all nutrient requirements.
- Report inoculant strain, colony-forming units or spore density, method of application and soil properties in research papers.

Conclusion

PSB and VAM improve nutrient dynamics in groundnut through complementary mechanisms. PSB mainly enhances phosphorus availability, which indirectly improves root growth, nodulation and biological nitrogen fixation. VAM expands the functional root zone through hyphal networks and therefore has a broader influence on nutrient uptake, water relations and K cycling. In groundnut, available N is expected to remain stable or increase slightly before harvest and may remain higher after harvest due to fixed N and decomposing root residues. Available K may decrease slightly before harvest because improved crop growth increases K uptake, but it can recover after harvest through residue decomposition and microbial mobilization. VAM generally shows stronger effects than PSB for both residual N and K when root development, moisture and microbial survival are favourable. The most publishable interpretation is therefore not a simple ranking of inoculants, but a process-based explanation supported by soil, plant uptake and yield data.

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