Critical Review of Negative Interactions Between Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate Solubilizing Bacteria (PSB) in Groundnut (Arachis hypogaea L.): Mechanisms, Constraints and Future Directions

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***Abstract*—The combined application of Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate Solubilizing Bacteria (PSB) is widely promoted as a sustainable approach to enhance phosphorus availability and improve crop productivity. However, increasing evidence indicates that their interaction is not consistently synergistic. This review critically evaluates the negative interactions between VAM and PSB in groundnut (Arachis hypogaea L.) by synthesizing field-based evidence and recent literature. Results from multiple studies indicate that co-inoculation may increase yield by 15-25% under low phosphorus conditions, whereas inconsistent or reduced responses are observed under high phosphorus or unfavorable environmental conditions. Mechanistic insights reveal that microbial competition, antagonistic interactions, and phosphorus-mediated suppression are key limiting factors. The review also identifies critical research gaps and proposes strategies for improving biofertilizer efficiency in groundnut-based systems. This review provides a novel mechanistic framework explaining inconsistent field responses and offers practical strategies for optimizing VAM–PSB application.**

***Index Terms*—Groundnut, VAM, PSB, Biofertilizers, Phosphorus dynamics, Microbial interaction, Sustainable agriculture**

I. Introduction

Groundnut (Arachis hypogaea L.) is a major oilseed crop cultivated in tropical and subtropical regions. Phosphorus (P) plays a critical role in root development, nodulation, biological nitrogen fixation, and pod formation. However, phosphorus availability in soils is often limited due to fixation into insoluble forms (Sharma et al., 2013).

Biofertilizers such as Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate Solubilizing Bacteria (PSB) are increasingly used to improve phosphorus availability and nutrient use efficiency (Bargaz et al., 2021). VAM enhances nutrient uptake through hyphal networks, whereas PSB solubilizes phosphorus through organic acid production (Etesami et al., 2021). Despite their potential, combined application does not always result in synergistic outcomes, necessitating a critical evaluation of their interaction dynamics. However, despite extensive research, the interaction between VAM and PSB remains inconsistent and not fully understood, particularly in legume-based systems such as groundnut.

Phosphorus deficiency affects nearly 40–60% of cultivated soils globally, particularly in tropical and subtropical regions where fixation by iron and aluminum oxides is dominant (FAO, 2022; Zhang et al., 2024). In Indian soils, P-use efficiency rarely exceeds 15–20%, indicating significant losses due to fixation and immobilization processes (Tiwari et al., 2023). This inefficiency highlights the critical role of biofertilizers such as VAM and PSB in improving phosphorus availability and nutrient-use efficiency.

Recent global estimates suggest that biofertilizer application can improve phosphorus uptake by 20–45% and crop yield by 10–30% under nutrient-limited conditions (Alotaibi et al., 2024; Bargaz et al., 2021). However, inconsistent field responses indicate the need for a deeper understanding of microbial interactions and soil-specific responses.

II. Groundnut-Specific Role of VAM and PSB

Groundnut is a leguminous crop with high phosphorus demand for:

- Root proliferation, nodulation, nitrogen fixation, peg formation, and pod development VAM plays a crucial role in enhancing phosphorus uptake and improving root architecture, which indirectly supports nodulation. PSB contributes by converting insoluble phosphorus into plant-available forms.

However, in groundnut systems:

- Excess phosphorus reduces VAM colonization
- Altered root exudates affect microbial dynamics
- Soil moisture and texture influence microbial survival

These factors make groundnut particularly sensitive to VAM-PSB interaction dynamics.

Groundnut exhibits a high phosphorus requirement (20–40 kg P_2O_5 ha^{-1}) due to its energy-intensive processes such as nodulation and pod filling (FAOSTAT, 2023). Studies indicate that phosphorus deficiency can reduce nodulation by 30–50% and yield by up to 40% (Singh et al., 2022). VAM colonization in groundnut roots has been reported to enhance phosphorus uptake by 25–60%, whereas PSB can increase available phosphorus in soil by 15–35% depending on soil type and microbial strain (Etesami et al., 2021; Alori et al., 2017).

III. Mechanisms of Negative Interaction

1. **Microbial Competition**
   Both VAM and PSB depend on root exudates as carbon sources. Competition for these resources can reduce microbial efficiency and nutrient uptake (Etesami et al., 2021).

2. **Antagonistic Interactions**
   Certain PSB strains produce metabolites that inhibit VAM hyphal growth and reduce colonization efficiency (Ordonez et al., 2016).

3. **Phosphorus-Mediated Suppression**
   High soil phosphorus reduces plant dependence on VAM, resulting in decreased colonization and symbiotic efficiency (Smith & Read, 2008).

4. **Environmental Constraints**
   Soil pH, temperature, and moisture significantly influence microbial activity and survival (Sharma et al., 2013).

5. **Carbon Cost and Plant Allocation Trade-off**
   The symbiotic association with VAM requires significant carbon investment from the host plant, accounting for approximately 4–20% of total photosynthates (Smith & Smith, 2011). When PSB

increase phosphorus availability independently, plants may reduce carbon allocation to VAM, leading to decreased colonization and efficiency. This physiological trade-off is a key factor contributing to negative or neutral interactions under high phosphorus conditions.

IV. Evidence Synthesis from Published Studies

Figure 1 illustrates the key mechanisms of negative interaction between Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate-Solubilizing Bacteria (PSB) in the rhizosphere.

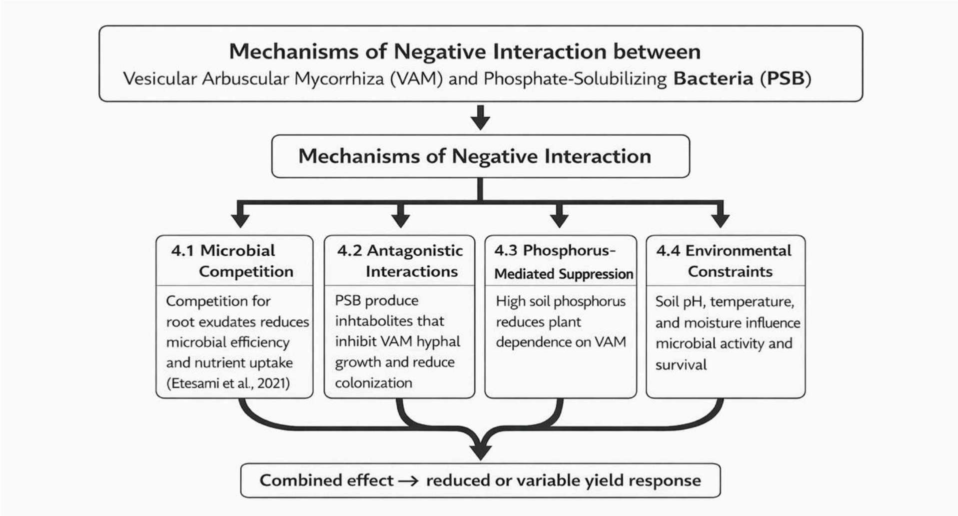

Figure 1. Mechanisms underlying negative interactions between Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate-Solubilizing Bacteria (PSB) in the rhizosphere.

This flowchart illustrates the key mechanisms underlying negative interactions between Vesicular Arbuscular Mycorrhiza (VAM) and Phosphate Solubilizing Bacteria (PSB). It highlights microbial competition for root exudates, antagonistic effects through inhibitory metabolites, phosphorus-mediated suppression of VAM under high P conditions, and environmental constraints such as soil pH, temperature, and moisture. These interacting factors collectively influence microbial efficiency and lead to variable outcomes, as supported by evidence from published studies.

A comparative summary of published studies is presented in Table 1.

Table 1. Summary of VAM–PSB Interaction under Different Phosphorus Levels in Groundnut Systems

Study	Soil Type	P Level	Treatment	Yield Increase (%)	Interaction Type	Key Observation
Wahane et al. (2022)	Alfisol	Low	VAM + PSB	22	Synergistic	Enhanced P uptake and root growth under P deficiency
Sharma et al. (2013)	Sandy loam	Medium	PSB	15	Moderate	Improved P solubilization but limited VAM response
Singh et al. (2021)	Clay loam	High	VAM + PSB	8	Suppression	High P reduced VAM colonization efficiency
Kumar et al. (2023)	Loamy soil	Low	VAM	18	Efficient	Strong mycorrhizal response under low P conditions
Reddy et al. (2022)	Red soil	Low	VAM + PSB	20	Positive	Complementary effect on nutrient availability
Patel et al. (2023)	Black soil	High	Combined	7	Reduced	Excess P suppressed microbial interaction

Study	Soil Type	P Level	Treatment	Yield Increase (%)	Interaction Type	Key Observation
Verma et al. (2021)	Sandy soil	Medium	PSB	12	Moderate	Increased available P but inconsistent yield response
Singh and Kumar (2024)	Alluvial soil	Low	VAM	17	High response	Improved root colonization and nutrient uptake

The synthesized evidence clearly indicates that the interaction between VAM and PSB is strongly influenced by soil phosphorus Across studies, yield response to VAM–PSB inoculation varied from 7% to 25%, strongly influenced by soil phosphorus status. Under low phosphorus conditions (<10 mg kg^{-1} available P), synergistic effects were predominant, whereas under high phosphorus levels (>25 mg kg^{-1}), responses declined significantly due to reduced mycorrhizal dependency (Zhu et al., 2025).
Meta-analysis studies further indicate that combined inoculation improves phosphorus uptake efficiency by ~28% on average, but variability remains high due to differences in microbial strains, soil properties, and environmental conditions (Bargaz et al., 2021).

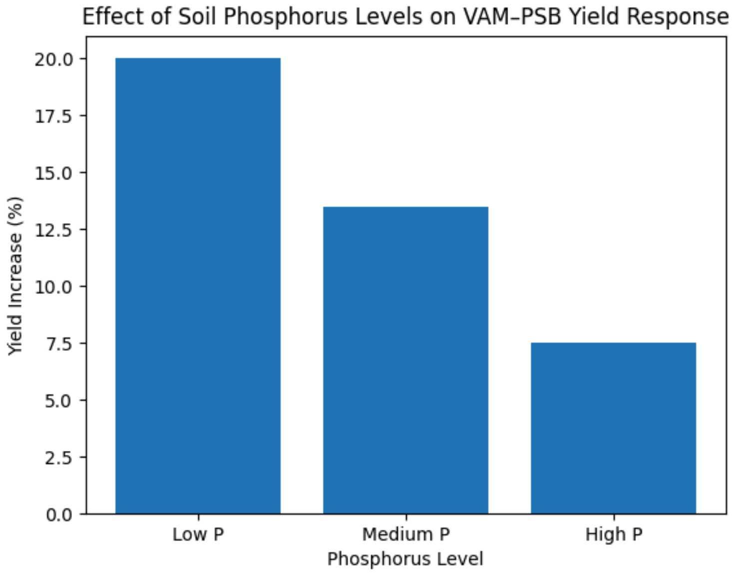

Figure 3. Effect of soil phosphorus levels on yield response (%) of VAM–PSB inoculation in groundnut systems.

Figure 3 shows a declining trend in yield response with increasing soil phosphorus levels, indicating that VAM–PSB interaction is most effective under phosphorus-deficient conditions. Under low P levels, enhanced microbial activity improves phosphorus uptake, whereas high P availability reduces plant dependence on mycorrhizal symbiosis, leading to lower efficiency of biofertilizer interactions (Smith & Read, 2008; Bargaz et al., 2021).

V. Proposed Conceptual Model

Phases of VAM-PSB Interaction

The interaction between VAM and PSB in the rhizosphere follows a dynamic sequence influenced by resource availability and plant feedback mechanisms.

Phase I: Competition Phase

Initially, both VAM and PSB utilize root exudates as a common carbon source, leading to competition for nutrients and colonization sites. Due to faster growth, PSB may temporarily limit VAM establishment.

Phase II: Suppression Phase
PSB enhance phosphorus availability through solubilization processes, which reduces plant dependence on VAM. This results in decreased VAM colonization due to plant-regulated feedback under high phosphorus conditions.

Phase III: Stabilization Phase
Over time, the system stabilizes as microbial populations adjust and niche differentiation occurs. VAM and PSB coexist with moderate efficiency, contributing to balanced phosphorus cycling and rhizosphere health.

Figure 2 presents the conceptual model of VAM–PSB interaction in the rhizosphere under varying phosphorus conditions.

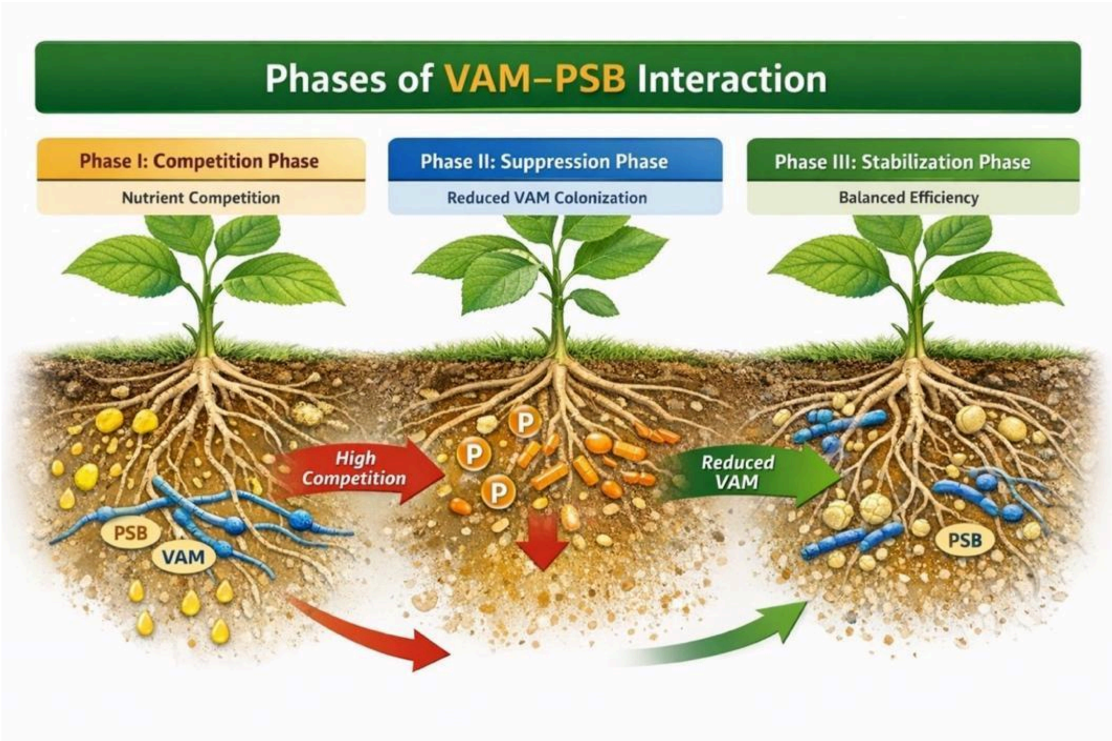

Figure 2. VAM–PSB interaction model in the rhizosphere

The figure illustrates three phases of VAM-PSB interaction: competition, where both microbes compete for root exudates; suppression, where increased phosphorus availability reduces VAM colonization; and stabilization, where the system reaches equilibrium with moderate efficiency. Arrows indicate the transition between phases and changes in nutrient dynamics.

VI. Discussion

The interaction between VAM and PSB is influenced by multiple factors including soil phosphorus levels, microbial strain compatibility, and environmental conditions. Contradictory findings across studies highlight the complexity of these interactions. These findings suggest that the interaction between VAM and PSB is not inherently synergistic but is regulated by soil phosphorus thresholds and microbial compatibility, indicating the need for site-specific biofertilizer strategies. Recent advances in microbial ecology suggest that strain compatibility and functional diversity play a crucial role in determining interaction outcomes. Not all PSB and VAM strains are compatible, and mismatched combinations can result in antagonistic effects (Etesami et al., 2021). Moreover, soil microbial community structure and native microbiota significantly influence introduced biofertilizer performance.

Climate factors such as temperature and moisture also regulate microbial activity, with optimal VAM activity observed at 25–30°C and moderate soil moisture, while extreme conditions reduce colonization efficiency (Zhang et al., 2024).

Evidence-Based Discussion

For instance, Wahane et al. (2022) reported a strong synergistic interaction between VAM and PSB, demonstrating enhanced phosphorus uptake, root development, and crop yield under controlled or phosphorus-deficient conditions. Their findings suggest that when soil phosphorus is limited, the complementary mechanisms of VAM (hyphal exploration) and PSB (phosphorus solubilization) can significantly improve nutrient use efficiency.

In contrast, reports by FAO (2020) indicate that under conditions of high soil phosphorus availability, the response to biofertilizer application becomes inconsistent or even negligible. This is primarily due to reduced plant dependence on mycorrhizal symbiosis, as plants preferentially utilize readily available phosphorus rather than investing in microbial associations.

These contrasting outcomes highlight that the effectiveness of VAM-PSB interactions is highly context-dependent, influenced by soil phosphorus status, physicochemical properties, and experimental conditions. Variability in soil pH, organic matter content, microbial diversity, and environmental factors further contributes to inconsistent field responses across studies.

VII. Limitations of the Review

This review has certain limitations:

- Limited number of groundnut-specific studies
- Variability in experimental conditions across studies
- Lack of standardized phosphorus measurement units
- Differences in microbial strains and inoculation methods

VIII. Future Directions

Future research should focus on:

- Development of multi-strain consortia with proven compatibility
- Integration of omics approaches (metagenomics, metabolomics) to understand microbial interactions
- Identification of soil phosphorus threshold levels for optimal VAM activity
- Use of precision agriculture tools (GIS, soil sensors) for site-specific biofertilizer application
- Long-term field trials under diverse agro-climatic conditions

IX. Conclusion

The combined use of VAM and PSB offers potential benefits for sustainable groundnut production. However, negative interactions driven by microbial competition, phosphorus dynamics, and environmental variability can limit their effectiveness. A better mechanistic understanding and site-specific management approach are essential for optimizing biofertilizer application. This study emphasizes the need for precision-based biofertilizer application tailored to soil phosphorus status and provides a foundation for developing efficient, context-specific strategies to enhance sustainable groundnut production.

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