

Effects of rhizobium and phosphate-solubilizing bio-fertilizers on growth and yield of fenugreek

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Abstract: Fenugreek (*Trigonella foenum-graecum* L.) is a multipurpose legume cultivated for its leaves and seeds. Its growth depends on adequate nitrogen and phosphorus nutrition, yet the availability of these nutrients is shaped by biological as well as chemical processes in soil. Compatible rhizobia form root nodules that can supply nitrogen through biological nitrogen fixation. Phosphate-solubilizing bacteria (PSB) can mobilize some forms of phosphorus that would otherwise be poorly available to roots. Their combined application is therefore of interest: phosphorus is needed for root development and the energy-intensive process of nitrogen fixation, while improved nitrogen nutrition can support foliage, flowering, and seed formation. This article critically reviews the proposed mechanisms and the available evidence concerning fenugreek growth and yield. Fenugreek-specific experiments have reported improved germination, biomass, nutrient uptake, or stress responses following treatment with selected beneficial bacteria. Research across other legumes provides support for studying interactions between rhizobia and phosphorus-mobilizing microorganisms. Nevertheless, responses depend on bacterial strain, host compatibility, soil properties, nutrient status, moisture, and inoculant quality. Early growth responses must not be treated as proof of increased seed yield, and results from other legumes cannot establish a fertilizer recommendation for fenugreek. The article proposes a field research framework that compares single and combined inoculation, evaluates both leaf and seed harvests, and measures soil and plant responses across seasons. Rhizobial and PSB inoculants offer a promising component of integrated fenugreek nutrition, provided that recommendations are based on reproducible local evidence rather than assumed benefits.

Keywords: Fenugreek; *Trigonella foenum-graecum*; Rhizobium; phosphate-solubilizing bacteria; bio-fertilizers; biological nitrogen fixation; nodulation; phosphorus availability; seed yield; sustainable agriculture

INTRODUCTION

Fenugreek occupies an interesting position among cultivated plants. It is a legume, a leafy vegetable, a seed spice, and a crop of interest to researchers studying plant composition. For a grower producing fresh leaves, rapid establishment and tender vegetative growth may be the immediate priorities. A grower producing seed must also secure successful flowering, pod development, and grain filling. Both production goals depend on the crop's ability to obtain nutrients throughout its life cycle. Its identity as a legume creates an additional possibility: part of its nitrogen requirement may be met through a beneficial relationship with root-

nodulating bacteria. Kew identifies *Trigonella foenum-graecum* as an accepted species with a native range extending from Iraq to northern Pakistan and a distribution far beyond that region.

Nitrogen and phosphorus influence different but connected aspects of plant performance. Nitrogen is needed for proteins, chlorophyll, and the development of photosynthetically active foliage. Phosphorus participates in energy transfer and is important for roots and reproductive growth. For legumes, phosphorus has a further role because biological nitrogen fixation requires considerable energy. A plant may therefore have suitable rhizobia near its roots yet fail to receive the full potential benefit of nodulation when phosphorus availability is inadequate. Conversely, providing phosphorus alone does not guarantee effective biological nitrogen fixation if the relevant bacterial partnership is weak. Reviews of legume nutrition identify this relationship as a strong reason to investigate rhizobia and phosphorus-mobilizing microorganisms together.

A bio-fertilizer, in the sense used here, is a preparation containing living beneficial microorganisms intended to improve nutrient acquisition or plant performance. Rhizobial inoculants introduce selected bacteria capable of forming a compatible association with a legume. PSB inoculants introduce microorganisms selected for their ability to mobilize phosphorus or perform associated plant-growth-promoting functions. These products do not work like a measured quantity of soluble fertilizer added directly to soil. Their effect requires the organisms to remain alive, establish themselves in a suitable location, interact with the crop and soil, and perform useful functions during the growing season. The distinction matters whenever a positive laboratory result is translated into a field recommendation.

Interest in bio-fertilizers is partly practical. Fertilizer inputs represent a cost to growers, and nutrient-use efficiency affects the economics of production. Inappropriate or excessive nutrient application may also produce avoidable environmental burdens. Microbial inoculation could help farmers obtain more value from the nutrients already present in soil and from carefully managed fertilizer inputs. That possibility should be examined through comparisons of yield, input costs, and soil outcomes. It would be premature to call an inoculant a complete substitute for fertilizer without experiments that test the proposed replacement under the soil conditions in question.

This article has three purposes. First, it explains the biological basis for applying rhizobial and phosphate-solubilizing inoculants to fenugreek. Second, it distinguishes findings observed in

fenugreek from supporting evidence obtained in other crops. Third, it identifies the measurements needed to determine whether an apparent growth benefit results in a dependable increase in marketable leaves or harvested seed. The discussion is a critical review of published literature; it does not present a new field experiment or claim original yield data.

HISTORICAL BACKGROUND

Fenugreek's agricultural history predates the scientific study of soil microorganisms by many centuries. It came to be cultivated across regions where its foliage and seeds had practical value, and its usefulness encouraged its movement beyond its native range. Kew records the species' native range as extending from Iraq to northern Pakistan and notes its formal publication by Linnaeus in 1753. The long cultivation of fenugreek established it as a crop of human interest, but historical knowledge of the plant did not explain the invisible biological processes that influence its nutrition. Farmers could observe vigorous or weak growth without knowing which microorganisms lived near the roots or how these organisms affected nutrient availability.

Scientific work on legumes gradually changed that understanding. Investigation of root nodules established that leguminous plants can form associations with bacteria capable of converting atmospheric nitrogen into forms useful to the plant. This finding gave agriculture a new way to think about nitrogen supply. Nutrient management was no longer confined to adding material to a field; it also involved encouraging an effective relationship between the crop and living organisms. Subsequent research showed that the presence of nodules and the performance of the nitrogen-fixing association depend on both partners and their environment. A legume's capacity for fixation is therefore a biological opportunity rather than an unconditional guarantee of adequate nitrogen nutrition.

The phosphorus problem followed a related path. Researchers found that soil may contain substantial phosphorus while providing too little in forms immediately accessible to roots. Studies of phosphate-solubilizing microorganisms explored how bacteria and fungi interact with mineral and organic phosphorus pools. Organic acids, enzymes, and changes in the chemical conditions around roots became important subjects of investigation. Work on rhizobial isolates also complicated a simple division between "nitrogen-fixing bacteria" and "phosphate-solubilizing bacteria": some rhizobial strains display phosphate-solubilizing

ability themselves. This encouraged strain-level evaluation rather than reliance on a broad microbial label.

As agricultural microbiology developed, attention shifted from identifying useful traits in a laboratory to delivering a dependable inoculant to farmers. Researchers had to consider whether a strain survived production and storage, remained viable on treated seed, colonized the rhizosphere, and performed well in soil containing competing native microorganisms. Such questions remain central today. An organism that dissolves phosphate on a culture plate may fail to provide a measurable field benefit when the soil contains a different phosphorus compound or when moisture limits microbial activity. Reviews of bio-fertilizer formulation describe this transition from isolation to practical application as a major challenge. frontiersin.org

Fenugreek-specific investigations added an important crop perspective. Researchers studying bacteria associated with fenugreek root nodules examined plant-growth-promoting traits and tested selected organisms with a rhizobial strain. Later work on seed bio-priming evaluated consortia of phosphate-solubilizing rhizobacteria and reported improvements in fenugreek germination and early growth under the conditions studied. More recent experiments have considered nutrient absorption, dry matter, drought, and salinity. Together, these studies show how research moved from the general concept of beneficial microbes toward questions about particular fenugreek responses. They also show why results should be described precisely: better seedling establishment, stronger vegetative growth, and increased mature seed yield are related but distinct outcomes.

FENUGREEK GROWTH AND ITS NUTRIENT REQUIREMENTS

Fenugreek passes through several stages at which nutrient availability can influence its eventual performance. Germination and establishment determine the initial plant stand. During vegetative growth, leaves and stems develop the photosynthetic capacity needed to support later flowering. Root growth determines the volume of soil from which water and nutrients can be obtained. Flowering and pod formation then determine how much of the plant's growth may become seed yield. A treatment that improves only one stage can still be valuable, but its agricultural significance depends on the crop's intended use and the conditions that follow.

For a leafy fenugreek crop, early establishment and vegetative biomass have direct commercial relevance. Uniform germination can make the stand easier to manage, and sufficient foliage contributes to a harvestable leaf yield. For a seed crop, early growth is a foundation rather than the final outcome. Vigorous plants may produce more reproductive sites, but they may also face later limitations from water shortage, heat, disease, or inadequate nutrition during pod filling. A scientific assessment should therefore state whether “yield” means fresh leaves, dry leaf material, pods, seeds per plant, seed weight, or seed yield per unit area.

Nitrogen supports the production of leaf proteins and chlorophyll. If effective rhizobial nodulation supplies part of the plant’s nitrogen, the crop may be less dependent on externally supplied nitrogen under suitable conditions. However, the amount fixed cannot be inferred from the crop’s legume status alone. It varies with the bacterial strain, the plant, soil conditions, and other available sources of nitrogen. A plant may produce nodules that are few, ineffective, or formed too late to supply a substantial share of its nitrogen requirement. Measurements of nodule activity and plant nitrogen status are consequently more informative than simply recording whether nodules are present.

Phosphorus availability has an equally important timing dimension. Young roots may explore only a small soil volume, making the concentration and movement of available phosphorus around the root especially relevant. As the plant develops, phosphorus is needed to support continued growth and reproductive processes. Yet soil phosphorus is distributed among pools with different degrees of availability. The fact that a soil test records phosphorus in one form does not mean that all phosphorus held in that soil can be used during the crop’s season. PSB are of interest because they may alter the availability of a portion of that pool, although the effect depends on soil chemistry and microbial activity.

The relationship between nutrient supply and yield is not necessarily linear. Adding or mobilizing more of a nutrient may have little benefit once the crop has enough of it, while a shortage of another nutrient or of water may continue to limit growth. This principle is important when interpreting inoculation trials. If a combined microbial treatment performs better than an untreated control, the result establishes a treatment effect under those conditions. It does not automatically show which microbial function caused the difference, whether nitrogen fixation increased, or whether the response will recur in a soil with a different fertility status.

RHIZOBIUM AND BIOLOGICAL NITROGEN FIXATION

Rhizobial bacteria are best known for their symbiotic association with legumes. Establishment begins when a compatible bacterium encounters a receptive root and a sequence of interactions permits infection and nodule formation. Within functioning nodules, bacterial nitrogen fixation converts atmospheric nitrogen into a form the plant can use. The plant, in turn, supplies resources derived from photosynthesis. The exchange can be highly useful, but it places demands on both partners. Effective fixation requires an appropriate bacterial strain, a responsive host, and growing conditions that support the association.

The term “Rhizobium inoculation” can obscure meaningful differences among products. Rhizobia are a diverse group, and a strain that performs well with one legume may not form an effective association with another. Even strains capable of nodulating the same host may differ in survival, competitiveness, and nitrogen-fixing performance. If a soil already contains effective native nodulating bacteria, an introduced strain must compete successfully before it can materially change the crop’s nutrition. Conversely, where compatible native populations are scarce or ineffective, inoculation may have greater scope to help. These possibilities explain why local evaluation is important for fenugreek.

An effective assessment of rhizobial inoculation should follow a chain of evidence. First, researchers can determine whether the inoculant remained viable at application. Second, they can evaluate plant establishment and the development of nodules. Third, they can examine whether nodulation corresponded with improved plant nitrogen status and biomass. Finally, they must measure the intended harvest. If these links are missing, the interpretation remains uncertain. For example, a greater number of nodules accompanied by no increase in plant nitrogen or yield raises a different question from an increase in both nodulation and harvested seed.

Research on fenugreek nodules provides a basis for this approach. Rajendran and colleagues examined nodule-associated bacteria with plant-growth-promoting characteristics and evaluated selected isolates in conjunction with a rhizobial strain. The work is relevant because it considers the organisms living in a fenugreek-associated environment and investigates combined microbial effects on plant growth. Its findings should be interpreted within its experimental system; they do not, on their own, establish a universal field-rate recommendation for all fenugreek cultivars and soils.

Rhizobial inoculation may also interact with conventional nutrient management. A grower cannot assume that applying more nitrogen fertilizer will always improve the value of inoculation. Legume responses to external nitrogen and symbiotic nitrogen fixation can interact in complex ways. The sensible research question is therefore how an inoculant performs within a complete nutrient-management plan. Trials that compare inoculation at several relevant fertilizer levels are more useful for practical decisions than trials that compare inoculated and uninoculated plants under only one unspecified fertility condition.

PHOSPHATE-SOLUBILIZING BACTERIA AND PHOSPHORUS AVAILABILITY

PSB are microorganisms capable of increasing the solubility or accessibility of certain phosphorus sources under appropriate conditions. The category describes a function rather than a single species. Bacterial groups investigated for phosphorus mobilization include members of *Bacillus*, *Pseudomonas*, and other genera; some rhizobial strains also exhibit this capacity. Sridevi and Mallaiah's examination of rhizobial isolates illustrates the latter point: the phosphate-solubilizing ability of the isolates varied. The practical implication is that the name of a bacterial genus cannot substitute for testing the specific strain proposed for use.

One pathway involves the release of organic acids that change chemical conditions near a phosphorus-containing mineral. Others involve compounds that bind elements associated with phosphorus or enzymes that help release phosphorus from organic material. The relative contribution of these processes depends on the microorganism and the forms of phosphorus present. Recent reviews emphasize that phosphorus transformation in soil is dynamic: microorganisms can contribute to mobilization, but they can also temporarily incorporate available phosphorus into their own cells. A simple laboratory measure of a clear zone around a colony therefore does not capture the entire soil–plant–microbe relationship.
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PSB may influence plant growth through more than phosphorus alone. Some isolates produce substances that affect root architecture, which can change the plant's ability to explore soil. Others have additional nutrient-mobilizing or stress-related traits. These multiple functions are scientifically interesting but make causal claims more difficult. If inoculated fenugreek develops longer roots and accumulates more phosphorus, one must still determine whether the change arose chiefly from mineral solubilization, altered root growth, another microbial trait,

or an interaction among them. A carefully designed experiment can measure several possible pathways instead of assigning every benefit to phosphate solubilization.

Fenugreek bio-priming research offers crop-specific evidence. Kumar and colleagues tested consortia of phosphate-solubilizing rhizobacteria and reported improvements in germination and growth measures for fenugreek under the experimental conditions. The study supports examining multi-strain treatments, particularly for seed establishment. It also demonstrates why descriptions of the outcome must remain exact. An improvement in germination, plant height, or plant weight is valuable evidence of a growth response; a claim about seed yield requires seed-yield data.

The choice of PSB strain should reflect the soil in which it will be used. Different soils hold phosphorus in different forms, and chemical conditions can influence microbial survival as well as phosphorus reactions. An isolate selected through tests using one phosphate source may not perform equally against the dominant poorly available phosphorus forms in a particular field. Laboratory screening is therefore a useful first stage, followed by pot work and field trials with measured soil conditions. Reviews of PSB effectiveness repeatedly identify this progression as necessary for converting a promising organism into an agronomically useful inoculant.

WHY COMBINED INOCULATION MAY BENEFIT FENUGREEK

The central reason for combining rhizobia and PSB is the relationship between phosphorus nutrition and nitrogen fixation. Nitrogen fixation requires energy, and nodule formation and function depend on adequate plant resources. If phosphorus availability restricts root growth or the processes sustaining active nodules, mobilizing some additional phosphorus could strengthen the crop's response to a compatible rhizobial inoculant. At the same time, improved nitrogen nutrition can support foliage that captures energy for continued growth. The two functions may therefore reinforce one another under conditions in which both nutrients constrain the crop.

This reasoning should be understood as a testable hypothesis. A combined treatment could outperform either single inoculant, equal the stronger one, or fail to improve growth. The result will depend partly on whether both strains establish near the root. It will also depend on whether their functions address an actual limitation. If soil phosphorus is already readily

available, adding a PSB strain may bring little further benefit. If an introduced rhizobial strain cannot compete with native organisms or is poorly matched to fenugreek, greater phosphorus availability may not produce the expected improvement in nitrogen fixation.

The organisms themselves may interact. Two strains selected separately for useful functions are not automatically suitable partners in the same formulation. One may grow faster in the carrier, reduce the survival of the other, or colonize a different part of the root environment. Their performance may also change after coating seed or entering soil. Compatibility testing should therefore examine both the formulation and the living plants. This is one reason research on multi-organism inoculants must go beyond combining two successful laboratory cultures.

Evidence from other legumes gives the hypothesis scientific support without eliminating the need for fenugreek trials. Reviews describe studies in which combinations of rhizobia and phosphorus-mobilizing bacteria improved nodulation, plant growth, nutrient uptake, or yield in crops such as soybean and chickpea. A synthesis of grain-legume work in Ghana likewise highlights the importance of evaluating inoculants together with phosphorus management and the characteristics of the local farming system. These results show that the combined approach is plausible and sometimes productive. They do not establish the magnitude of a fenugreek response in any particular district or season.

For fenugreek, the most useful question may be whether combined inoculation produces an additional benefit beyond good conventional management. Farmers make decisions among real options: using a tested inoculant, applying fertilizer according to soil need, combining the two, or following existing practice. An experimental comparison should represent these options fairly. If the combined treatment improves yield only against an untreated, severely nutrient-limited control but adds little to a well-managed treatment, its practical value will differ from a treatment that improves yield or reduces costs under normal farm conditions.

EVIDENCE FROM FENUGREEK STUDIES

Fenugreek-specific research is essential because the crop is grown for different harvests and in varied environments. The study by Rajendran and colleagues investigated nodule-associated *Exiguobacterium* isolates and their possible contribution to plant growth when evaluated with a rhizobial strain. The importance of this work lies in its examination of microorganisms

connected to fenugreek nodules and its attention to interactions among beneficial bacteria. It suggests research directions for combined inoculation, although its controlled experimental conditions must be considered before extrapolating to large-scale seed production.

Kumar and colleagues assessed seed bio-priming with phosphate-solubilizing rhizobacterial consortia in fenugreek and tomato. In the fenugreek component, particular consortia improved germination and measured plant-growth characteristics. Such a result has immediate relevance to crop establishment: a more uniform and vigorous stand may give plants a stronger start. Yet the relationship between initial vigour and final seed yield depends on subsequent conditions. Competition among plants, weather, irrigation, nutrient supply, and reproductive success can all influence what happens after the seedling stage.

Solouki and colleagues examined seed bio-priming and plant-growth-promoting bacterial applications in relation to fenugreek morphology, nutrient absorption, and dry-matter production. Their work broadens attention from germination alone to the development of plant material and nutrient status. It also illustrates a challenge in interpreting combined treatments: when bio-priming is used alongside other applications, the experiment must distinguish the effect of each component from that of the complete package. Factorial designs are particularly useful because they allow researchers to examine both separate effects and interactions.

Research under environmental stress asks another question. Patel and colleagues studied *Bacillus subtilis* ER-08 in fenugreek under drought and salinity conditions and reported improvements in growth and nutrient status associated with treatment. This organism is not interchangeable with a rhizobial inoculant, and the experiment should not be presented as direct proof that Rhizobium-plus-PSB will raise fenugreek seed yield. It does, however, show why strain traits and environmental conditions deserve attention. An inoculant that performs well in favourable conditions may be less useful if it fails during the water stress commonly experienced by a crop.

Fenugreek has also been investigated in intercropping systems involving growth-promoting bacteria and mycorrhiza. A study in Iran evaluated agronomic and oil-related outcomes under different cropping and microbial treatments. Its relevance to the present topic is comparative: microbial responses can be influenced by crop arrangement and the wider biological system, while seed and oil outcomes need separate measurement. It cannot isolate the effect of a

particular Rhizobium-plus-PSB combination unless that combination is expressly included and compared in the design.

Taken together, the fenugreek literature offers encouraging evidence for microbial approaches, especially for establishment, nutrient uptake, biomass, and responses under selected conditions. It also reveals a research gap. Results from different microbial species, application methods, soil environments, and harvest goals are sometimes discussed as though they answered the same question. They do not. To assess the proposed combination in this article, researchers need direct comparisons using identified compatible rhizobial and PSB strains, with harvest-stage outcomes reported for fenugreek.

EFFECTS ON GROWTH, NODULATION, AND YIELD COMPONENTS

Germination and establishment: A microbial seed treatment places the organism close to the emerging root, where early interaction becomes possible. Improved germination or seedling growth can be particularly meaningful when poor establishment reduces plant density. Researchers should record both laboratory germination and field emergence because conditions differ substantially. A treatment that performs well under controlled moisture and temperature may produce a smaller response in a dry or biologically competitive field. The fenugreek bio-priming study provides a basis for testing this stage systematically.
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Root development. Roots determine how effectively a plant explores soil for water and nutrients. Beneficial microorganisms may affect root length, branching, or the immediate conditions around the root. Better phosphorus access could support root development, while a larger root system could in turn create more opportunities for microbial colonization. Because these relationships can operate in both directions, measuring only final root length is insufficient to identify the main cause. Observations at several stages can help show whether changes in root growth precede or follow changes in nutrient uptake.

Nodulation: A combined treatment should be evaluated for its effect on the number, development, and effectiveness of fenugreek nodules. More nodules are not necessarily better if they are small, inactive, or formed late. A useful study would pair nodule observations with plant nitrogen measures and biomass. If PSB improves phosphorus nutrition and nodule function, the evidence should show a coherent relationship among these variables. The legume

literature provides the rationale for examining such a relationship, while the actual effect in fenugreek remains a matter for direct testing.

Vegetative biomass and leaf yield: A vigorous, adequately nourished fenugreek plant may develop more harvestable foliage. For fresh-leaf production, researchers should measure marketable leaf mass and harvest timing, not merely total plant height. Height can increase without a proportionate gain in the edible portion. If repeated leaf harvests are part of the local production practice, researchers should also examine regrowth and the cumulative harvest. These outcomes may respond differently from seed yield because harvesting foliage changes the plant's subsequent growth and allocation of resources.

Flowering and pods: Greater vegetative growth provides a potential foundation for reproductive development, but environmental conditions around flowering can determine whether that potential becomes yield. Trials should measure flowering time, pod number, seeds per pod, and seed filling where feasible. A treatment might increase biomass without increasing pods, or increase pods without increasing seed weight. Distinguishing these patterns identifies where a response occurs and prevents a vague claim of "yield improvement" from hiding an unchanged final harvest.

Seed yield and quality: Seed yield per unit area is the decisive outcome for a seed-production recommendation. Researchers should report harvested area, plant population, moisture basis, and statistical variation. Seed size and relevant quality characteristics may also matter to the intended market. A nutrient-management strategy is most useful when it improves an outcome that farmers can sell or use, and when that gain is sufficiently consistent to justify the cost and work of inoculation.

SOIL, CLIMATE, AND INOCULANT QUALITY

The performance of a microbial inoculant begins before sowing. The production process must provide a viable population of the intended strain. Packaging and storage then have to protect that population until use. If too few viable cells reach the seed or soil, the biological explanation for using the product may remain sound while the field treatment fails. Reviews of microbial formulation identify carrier selection, survival, shelf life, and practical delivery as central issues in turning promising strains into useful bio-fertilizers.

Application method affects where the microbes begin their interaction with the crop. Seed coating can place cells near the emerging root; other approaches introduce them into soil or through irrigation-related applications. Each method has practical requirements. A seed treatment must maintain seed viability, distribute the inoculant reasonably evenly, and avoid handling conditions that destroy the microorganisms. Where multiple products are used, their compatibility during mixing and application should be checked. Research reports should describe these procedures so that another investigator or grower can reproduce the treatment.

Soil properties shape the result after sowing. Soil pH and the chemical form of phosphorus affect how much phosphorus can become available. Organic matter, moisture, and the existing microbial community influence survival and competition. A strain selected for laboratory phosphate solubilization may encounter a field soil in which its preferred substrate is scarce, its growth is restricted, or native organisms perform similar functions. These possibilities explain why a trial should report baseline soil conditions rather than only treatment labels and final yield.

Water availability is particularly important because plant growth and microbial activity both respond to moisture. Under drought, roots have less opportunity to acquire nutrients, and the behaviour of the rhizosphere changes. Under excessive moisture, other constraints may emerge. Salinity introduces further physiological challenges. Fenugreek research with a multifunctional *Bacillus* strain under drought and salinity indicates that some microbial treatments can affect plant responses to stress, but it also reinforces the need to test the exact proposed organisms in the target environment.

Inoculant quality and soil suitability are distinct questions. A well-manufactured product may yield little benefit where the crop is not nutrient-limited or the strain is poorly adapted. Conversely, a highly responsive soil and cultivar cannot compensate for a product that has lost viability. Field research should therefore document both the properties of the field and the condition of the inoculant used. Without this information, a failure may be wrongly attributed to the biological approach, while a success may be difficult to repeat.

A RESEARCH FRAMEWORK FOR FENUGREEK

A strong fenugreek experiment would begin with a clearly defined production goal: fresh leaves, dry foliage, or seed. The selected cultivar and sowing conditions should suit that goal.

Before choosing inoculants, researchers should characterize the field's soil and establish whether compatible native rhizobia are present. Rhizobial strains should be tested for effective association with fenugreek, while candidate PSB should be evaluated against relevant phosphorus sources. Their compatibility should be examined before combined use.

The central comparison should contain an uninoculated control, Rhizobium alone, PSB alone, and Rhizobium plus PSB. These four treatments allow an investigator to distinguish the performance of each inoculant from the combined treatment. Where resources permit, the same comparison can be conducted at different, agronomically relevant phosphorus levels. If the study aims to determine whether fertilizer can be reduced, it must include appropriate full-rate and reduced-rate fertilizer comparisons. A reduction cannot be justified merely because an inoculated plant outperformed an unfertilized control.

Replicated field plots and suitable randomization are needed because fields vary even within a single location. Multiple sites or seasons provide a more demanding test of consistency. Researchers should record rainfall or irrigation and relevant weather events, as these may explain differences among seasons. The condition and application rate of each inoculant should also be reported. Measuring the crop at several stages establishment, vegetative growth, flowering, and harvest can reveal where the treatment first produces an effect and whether that effect persists.

Plant measurements should match the proposed mechanism. To assess a rhizobial effect, observe nodulation and plant nitrogen status. To assess PSB, examine plant phosphorus uptake alongside available soil phosphorus, while recognizing that a single soil test may not represent every process occurring near roots. Growth measurements can include emergence, height, root characteristics, leaf area, and biomass. Harvest measurements should include the appropriate leaf or seed yield. Quality measurements may be added when they matter to the crop's intended use.

The analysis should report variability and the statistical basis for comparing treatments. An observed difference in plot averages is not sufficient by itself to establish a dependable effect. Researchers should also examine whether the combination performs better than each single inoculant, because that is the central practical claim. If combined inoculation equals the better single treatment, the extra product or application step may not be justified. Economic

assessment should consider inoculant cost, application labour, any change in fertilizer expenditure, and the value of additional marketable produce.

Finally, findings should be stated at the level the evidence permits. One controlled trial can identify a promising treatment. Repeated field success across locations and seasons can support a more general recommendation. A strain that works in one location may need further validation elsewhere. This measured progression is consistent with broader reviews showing that crop genotype, inoculant, phosphorus management, and soil conditions interact in determining legume responses.

INTERNATIONAL PERSPECTIVES

International work on legumes offers both encouragement and caution for fenugreek researchers. A synthesis of studies under Ghanaian soil conditions examined grain-legume yield responses to rhizobial inoculation and phosphorus supplementation. Its emphasis on combined management and variable responses is relevant beyond the crops directly reviewed. It suggests that the most useful question is often not whether an inoculant can work in principle, but under which combination of crop, soil, and nutrient practices it produces a worthwhile result. Fenugreek research in India or elsewhere can apply that reasoning while collecting its own crop-specific evidence.

Reviews drawing on research across multiple countries describe a wide diversity of phosphorus-mobilizing microorganisms and mechanisms. They also identify a recurring gap between laboratory screening and field performance. Local soil chemistry can change which phosphorus sources matter, while temperature and moisture can affect microbial establishment. An isolate chosen from one environment may be valuable in another, but its performance should be verified there. International exchange of strains and methods is most useful when accompanied by transparent descriptions of field conditions and comparable outcome measures.

Fenugreek work itself illustrates how production systems alter the research question. The Iranian intercropping study involving microbial treatments assessed outcomes within a particular crop arrangement, including seed- and oil-related measures. A monocropped seed field, a fresh-leaf production system, and an intercropped field may each value different results. Consequently, “best treatment” cannot be separated from the system and the product

being harvested. International perspectives should widen the range of test conditions without erasing those distinctions.

For research to travel usefully across borders, reporting standards matter as much as positive results. Full strain identities, viable inoculant counts, soil descriptions, treatment combinations, replication, and harvest methods make studies comparable. Negative and inconsistent results should also be reported: they help identify where microbial products do not establish or where nutrient limitations are different from those expected. A more complete international evidence base would make it easier to select fenugreek strains for targeted field testing and harder to overstate a single favourable result.

CONCLUSION

Rhizobial and phosphate-solubilizing bio-fertilizers address two connected aspects of fenugreek nutrition. Compatible rhizobia can support nitrogen fixation through effective root nodules, while suitable PSB may increase the accessibility of some soil phosphorus and influence root development. Because phosphorus is important to the functioning of nitrogen-fixing legumes, combined inoculation has a credible biological basis. Fenugreek experiments with beneficial bacteria have reported encouraging responses in establishment, biomass, nutrient status, and performance under selected conditions. Evidence from other legumes further supports investigating coordinated nitrogen and phosphorus management.

The evidence does not justify assuming that every *Rhizobium*–PSB combination will increase fenugreek seed yield or replace a fixed proportion of fertilizer. Strain compatibility, viable delivery, existing soil microorganisms, phosphorus status, moisture, and the intended harvest can all alter the result. The appropriate conclusion is therefore specific: combined microbial inoculation is a promising research and management option whose agronomic value must be demonstrated with replicated, harvest-stage comparisons. Such research can support more efficient nutrient use while giving fenugreek growers recommendations grounded in their actual production conditions.

FUTURE SCOPE

Future work should prioritize the selection of rhizobial strains that form effective nodules with fenugreek cultivars and PSB strains that mobilize phosphorus sources relevant to local soils. Laboratory tests should establish whether candidate organisms remain compatible when

placed together in a formulation. Pot experiments can then examine root colonization, nodulation, and nutrient uptake before the combination advances to field trials.

Multi-location and multi-season field studies should compare untreated plants, each single inoculant, and the combined treatment. They should assess both fresh-leaf and seed-production systems where those uses are locally important. To test fertilizer savings, researchers should include defined fertilizer-rate treatments and calculate both yield and economic returns. Investigations of storage life, application methods, and performance under drought or salinity would address practical barriers to adoption. Finally, studies should publish complete methods and results, including weak or absent responses, so that future recommendations reflect the full range of field evidence.

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