

Bio-fertilizers as a sustainable alternative to chemical fertilizers: an assessment of growth, nutrient uptake and soil health in fenugreek cultivation

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Abstract: Fenugreek (*Trigonella foenum-graecum* L.) is cultivated for its edible leaves and seeds, making reliable growth and nutrient supply important to both vegetable and seed production. Bio-fertilizers containing beneficial microorganisms have been proposed as a means of improving nutrient availability while reducing dependence on chemical fertilizers. This article evaluates that proposition through three connected outcomes: fenugreek growth, nutrient uptake, and soil health. Rhizobial inoculants can support biological nitrogen fixation in compatible root nodules, while phosphate-solubilizing bacteria can mobilize some poorly available phosphorus. Other plant-growth-promoting bacteria may influence root development and nutrient acquisition. Fenugreek field studies in Rajasthan and Gujarat report benefits from selected microbial treatments, including combined Rhizobium and phosphate-solubilizing bacterial inoculation. They also reveal variation: one Jobner study recorded its highest seed yield and returns from inorganic nitrogen alone, while other studies favoured integrated organic, microbial, and mineral nutrient treatments. Bio-fertilizers therefore have potential as part of a sustainable nutrient-management strategy, but their capacity to replace a particular fertilizer input cannot be assumed. Evidence of soil health requires measurements extending beyond crop yield, including soil organic carbon, available nutrients, microbial activity, and the performance of subsequent crops. The article concludes that locally adapted inoculants, sound organic-matter management, soil testing, and replicated field evaluation offer a more defensible route to reducing unnecessary chemical inputs than a universal claim of complete replacement.

Keywords: Fenugreek; *Trigonella foenum-graecum*; bio-fertilizers; chemical fertilizers; Rhizobium; phosphate-solubilizing bacteria; nutrient uptake; soil health; integrated nutrient management; sustainable cultivation

INTRODUCTION

Fenugreek is a crop with several agricultural identities. Its tender foliage is consumed as a leafy vegetable, while its mature seeds are harvested as a spice and for other uses. These different products place different demands on crop management. A leaf crop depends heavily on establishment, vegetative growth, and the production of marketable foliage. A seed crop must maintain sufficient growth through flowering, pod development, and seed filling. In

either case, the crop must acquire nutrients from a soil environment whose biological and chemical properties vary across fields and seasons.

Fertilizers are commonly used to correct nutrient shortages and improve crop performance. Mineral or chemical fertilizers can supply nutrients in defined quantities, often with a relatively predictable immediate effect when applied appropriately. Yet a fertilizer recommendation based only on the amount placed in the field may overlook how much the crop actually obtains and what happens to the soil over repeated seasons. The central question for sustainable cultivation is how to maintain useful yields while managing nutrient sources efficiently and preserving the soil's capacity to support future crops.

Fenugreek's membership of the legume family makes microbial nutrient management particularly relevant. Compatible rhizobia can form nodules on roots and contribute nitrogen through biological nitrogen fixation. Phosphate-solubilizing bacteria (PSB) can transform or mobilize some forms of soil phosphorus that plants otherwise obtain with difficulty. Phosphorus also supports the energy-demanding process of nitrogen fixation. This creates a biological reason to investigate the two groups together. Other beneficial microorganisms may alter root growth or nutrient acquisition through additional mechanisms. These possibilities have led researchers to study bio-fertilizers alone and in combination with organic manures and mineral fertilizers.

The word **alternative** in the title needs careful interpretation. It may mean complete substitution of one nutrient source for another, partial replacement of a mineral fertilizer rate, or an additional practice that improves the efficiency of an existing program. Those are different claims requiring different evidence. An inoculant that increases seed yield when added to a full fertilizer program has demonstrated a benefit under that program. It has not thereby demonstrated that half the fertilizer can be removed. A trial comparing inoculation at both full and reduced fertilizer rates is needed to establish a defensible replacement claim.

This distinction is especially important because published fenugreek results are not uniform. At Udaipur, a study comparing cultivars, fertilizer levels, and microbial inoculations reported advantages for combined Rhizobium and PSB inoculation while also finding a strong response to the higher fertilizer level studied. At Jobner, another field study found that inorganic nitrogen alone produced the highest seed yield and economic return among its treatments, even

though the addition of manure and Rhizobium improved several growth measures. Other work at Jobner and in Gujarat identified productive combinations of organic and inorganic inputs or organic amendments with microbial inoculation. Together, these findings support investigation of integrated management while resisting a simple claim that a bio-fertilizer always replaces chemical fertilizer.

The present article assesses fenugreek cultivation through three related questions. Can bio-fertilizers improve plant growth and harvested yield? Do they increase the amount of nutrients absorbed by the crop or improve nutrient-use efficiency? Can they contribute to soil health in ways that remain useful beyond one harvest? The discussion draws on fenugreek-specific field experiments and wider research on microbial nutrient processes. It is a review and analysis of existing literature; it does not report original experimental observations.

HISTORICAL BACKGROUND

Fenugreek has been cultivated for far longer than the scientific disciplines now used to explain its nutrition. The plant moved across regions because people valued its leaves and seeds, and its continuing cultivation reflects its usefulness in diverse food and agricultural systems. The Royal Botanic Gardens, Kew, identifies the species' native range as extending from Iraq to northern Pakistan and records its formal description by Linnaeus in 1753. For much of fenugreek's agricultural history, growers could observe differences in plant vigour and harvest without knowing the identity of the microorganisms living near its roots.

Modern understanding of legume nutrition developed as scientists investigated root nodules and their relationship with atmospheric nitrogen. Biological nitrogen fixation showed that a crop could obtain some nitrogen through a partnership with microorganisms, provided the host plant and bacterial strain were compatible and the environment supported the process. This discovery widened the meaning of fertility. The quantity of nutrients supplied directly to soil remained important, but so did the biological processes through which nutrients became available to roots. Rhizobial inoculation grew from this understanding and became one of the best-known examples of a microbial agricultural input.

Research on phosphorus revealed another limitation in conventional thinking. A soil can contain phosphorus in appreciable amounts while still supplying too little in forms the crop can absorb during a particular season. Investigators identified microorganisms capable of

solubilizing certain mineral phosphates or contributing to the release of phosphorus from organic materials. As the mechanisms became clearer, scientists examined organic-acid production, enzymes, and the complex interactions of bacteria, roots, minerals, and soil chemistry. The resulting interest in PSB reflected a practical hope: some nutrient already present in a field might be used more effectively rather than continually increasing external inputs.

The development of mineral fertilizers changed agricultural production by allowing relatively precise nutrient supply. It also created an important comparison for microbial approaches. A living inoculant cannot be assessed solely by the quantity of a nutrient it contains, because its intended effect occurs through biological activity after application. Its success depends on viable cells, root colonization, competition with native organisms, moisture, soil chemistry, and the form of the nutrients it is expected to mobilize. Research therefore moved from identifying useful microbes in a laboratory to producing formulations that survive storage and perform consistently in farmers' fields.

Fenugreek field research brought these ideas into crop-specific nutrient management. Experiments in Rajasthan and Gujarat tested combinations of mineral nutrients, manures, Rhizobium, and PSB. Their differing results provided an important lesson: biological and chemical inputs cannot be ranked reliably without reference to the soil, cultivar, harvest goal, and treatments compared. Later research included seed bio-priming, nutrient uptake, soil properties, and environmental stress. The history of fenugreek bio-fertilizer research is thus a progression from recognizing beneficial microorganisms to asking where, how, and at what economic value they work. That final question remains the most relevant one for sustainable cultivation.

UNDERSTANDING BIO-FERTILIZERS IN FENUGREEK CULTIVATION

A bio-fertilizer is generally understood as a preparation containing living microorganisms applied to a seed, plant, or soil to improve nutrient availability or plant growth. Its function must be distinguished from that of farmyard manure, compost, or a mineral fertilizer. A manure supplies organic material and nutrients as it decomposes. A mineral fertilizer supplies measured chemical forms of nutrients. A microbial inoculant introduces organisms selected to

carry out useful biological processes. These inputs may be combined, but they should not be treated as identical merely because all can affect crop performance.

For fenugreek, rhizobial inoculants are particularly relevant because the crop is a legume. An effective bacterial strain may establish in root nodules and contribute nitrogen to plant growth. PSB inoculants address a different issue: the accessibility of phosphorus held in forms that roots cannot readily use. Some bacteria possess additional traits, such as producing substances that alter root architecture or helping the crop respond to stress. A multi-strain inoculant seeks to combine beneficial functions, but its label does not prove that the strains remain compatible or active after application.

The expected benefits can be stated as a sequence rather than a promise. A viable inoculant must reach the seed or root. It must survive and establish in the field. Its biological activity must then relieve a limitation experienced by the crop. That change should be detectable in plant nutrient status, growth, or both. Finally, it must contribute to a useful outcome such as marketable leaves, seed yield, improved nutrient efficiency, or a measurable soil benefit. A failure at any point can break the sequence even if the organism performed well in a laboratory.

This is why bio-fertilizer selection requires more than choosing a familiar microbial name. Sridevi and Mallaiah found variation in phosphate solubilization among rhizobial isolates. The observation illustrates that strains within a broad category may perform differently. Likewise, an isolate capable of dissolving one phosphate compound in a culture medium may not address the dominant nutrient constraint in a particular fenugreek field. Strain identification and soil characterization are therefore essential parts of a credible recommendation.

CHEMICAL FERTILIZERS AND THE MEANING OF SUSTAINABLE REPLACEMENT

Mineral fertilizers can be highly useful when soil nutrient supply does not meet crop demand. Their principal advantage is that an application can deliver a known quantity of nutrient at a chosen time. Fenugreek field experiments confirm that mineral nutrient levels can substantially affect growth, yield, and nutrient uptake. In the Udaipur study by Singh and colleagues, the higher nitrogen and phosphorus level tested improved yield and plant nutrient uptake compared with the lower level and untreated control. Mehta and colleagues likewise

reported gains from the higher nitrogen and phosphorus treatments in Gujarat. Such findings should remain visible in any balanced evaluation of bio-fertilizers.

A sustainable approach does not require denying those benefits. It asks whether nutrient inputs are matched to crop need, whether losses and unnecessary applications can be avoided, and whether soil properties are maintained over time. Bio-fertilizers may contribute if they increase the proportion of nutrients available to the crop, improve biological nitrogen supply, or enable a lower mineral fertilizer rate without sacrificing yield. Each proposition must be measured separately. A reduction in chemical input that lowers yield substantially may be unacceptable to a grower, while a treatment that maintains yield at lower cost could be valuable.

The distinction between nutrient **supply** and nutrient **mobilization** matters here. A PSB strain may help release phosphorus from a soil pool, but it does not create phosphorus from nothing. If a cropping system continually exports phosphorus in harvested products without replenishment, mobilization alone cannot maintain the overall nutrient balance indefinitely. Similarly, biological nitrogen fixation can introduce nitrogen from the atmosphere, but its effectiveness depends on a functioning crop–bacterium association. Sound nutrient management needs to account for inputs, removals, and changes in soil reserves rather than focusing on a single season’s response.

Organic materials add another dimension. Farmyard manure, compost, poultry manure, vermicompost, and oilseed cakes supply nutrients in forms and quantities that vary with their composition. They can also add organic matter that affects soil structure and biological activity. A beneficial outcome from “bio-fertilizer plus manure” cannot be attributed wholly to the microbial inoculant. The manure may supply nutrients directly, change moisture retention, or create a more favourable environment for microbes. Proper experiments include separate treatments if they aim to identify each contribution.

The Jobner study of integrated nutrient management is particularly useful because it complicates an overly simple account. Some measures of growth were higher where inorganic nitrogen, Rhizobium, and farmyard manure were combined. Yet the highest seed yield and economic return in that experiment occurred with inorganic nitrogen alone. The finding does not establish that microbial inputs are ineffective; it shows that different outcomes within the

same trial may favour different treatments. A sustainable recommendation should consider the crop's harvested product, the farmer's costs, and the state of the soil, rather than selecting a treatment solely because one growth variable improved.

EFFECTS OF BIO-FERTILIZERS ON FENUGREEK GROWTH

The first possible benefit of an inoculant appears during establishment. Seed-associated microorganisms are positioned close to the emerging root, where they may interact with the young plant. Germination percentage, speed of emergence, and the uniformity of the stand influence later crop development. Kumar and colleagues tested seed bio-priming with consortia of phosphate-solubilizing rhizobacteria and reported improved germination and growth measures in fenugreek for selected consortia. The result supports further work on seed treatments, but laboratory or early growth responses must be followed to harvest before conclusions are drawn about final seed yield.

Root development is a second pathway. A larger or more effectively branched root system can explore more soil for water and nutrients. Microbial processes may contribute by improving local nutrient availability or by producing substances that influence root growth. The effect can also run in the other direction: vigorous roots provide more surfaces and exudates that support microorganisms. Because these processes occur together, an observed increase in root length should not automatically be described as proof that phosphate solubilization alone caused the change. Measuring plant phosphorus status alongside root traits can offer a stronger interpretation.

Rhizobial inoculation may become more visibly relevant as nodules develop. Effective nodules can support nitrogen nutrition, contributing to foliage, branches, and total biomass. Bairva and colleagues, in a fenugreek field experiment at Ajmer, reported that dual *Rhizobium* and PSB inoculation improved several growth and nodule measures compared with other inoculation treatments. They also recorded higher seed and biological yield for dual inoculation than for the uninoculated control in that study. The experiment included plant growth regulator treatments, so its factorial design and treatment-specific comparisons matter when interpreting each reported result.

Growth must nevertheless be assessed in relation to the intended harvest. A tall fenugreek plant is not necessarily the most productive leaf crop if much of its biomass is unmarketable

stem. Nor does more vegetative biomass necessarily produce more mature seed. Researchers should measure fresh and dry leaf yield where foliage is the product, and pod number, seeds per pod, seed weight, and area-based seed yield where seed is the product. An inoculant that improves early leaf production may be valuable for one purpose even if it has little effect on another.

The Udaipur study offers an example of why the cultivar belongs in this assessment. Singh and colleagues compared two fenugreek varieties at fertilizer and inoculation levels and found differences in yield and soil nutrient status between cultivars. The superiority of dual inoculation in their experiment therefore sits within a wider interaction among genetic material, nutrient input, and microbial treatment. A formulation recommended for one cultivar cannot automatically be assumed to give an identical return with another.

NUTRIENT UPTAKE: FROM SOIL AVAILABILITY TO PLANT USE

Nutrient uptake links a soil-management practice with plant performance. Researchers commonly examine the concentration of a nutrient in plant tissue and the total quantity removed in the harvested crop and remaining biomass. The two measures answer different questions. A high tissue concentration does not necessarily imply high total uptake if the plant produced little biomass. Conversely, a larger plant can take up more nutrient even when the concentration in each unit of tissue changes little. The most informative fenugreek studies examine both yield and nutrient content.

Rhizobial inoculation is expected to affect nitrogen nutrition where a suitable association forms. Nitrogen-fixing nodules require the plant to invest resources, and their effectiveness depends in part on the availability of other nutrients. Phosphorus has particular importance because biological nitrogen fixation is energy-intensive. A PSB treatment may therefore influence nitrogen uptake indirectly if it improves phosphorus availability enough to support root and nodule function. That explanation is biologically plausible, but a specific experiment should measure nodulation, phosphorus status, and nitrogen uptake before presenting it as the established cause of a yield response.

Fenugreek field studies provide more direct evidence on the outcomes. Mehta and colleagues evaluated nitrogen, phosphorus, and bio-fertilizer treatments at Sardarkrushinagar. Their factorial experiment compared an uninoculated control with Rhizobium, PSB, and combined

inoculation. The study reported the highest measured yield and nutrient uptake with combined inoculation among its bio-fertilizer treatments, while higher tested rates of mineral nitrogen and phosphorus also improved performance. This pattern is consistent with complementary biological and mineral nutrient management under the experimental soil conditions. It does not show that mineral inputs can be omitted without a separate comparison designed to test omission.

Nutrient uptake also differs among plant parts. Aishwath and colleagues reported differences in nutrient accumulation between fenugreek seed and straw in their field study of manures and Rhizobium. Such differences matter when considering nutrient removal. If seed is sold but straw remains on the farm or is returned to soil, the longer-term nutrient balance differs from a system in which the entire above-ground plant is removed. Studies of soil health should therefore describe what happens to crop residues rather than treating all harvested biomass as though it leaves the field in the same way.

Solouki and colleagues investigated seed bio-priming and other applications of plant-growth-promoting bacteria in fenugreek, examining nutrient absorption and dry matter. Their work adds a physiological perspective to field-yield studies. At the same time, combinations of bio-priming, microbial application, and foliar nutrients must be separated analytically: an improved response to the full combination does not establish the isolated effect of any one component. Factorial research designs are especially useful because they can estimate both individual treatment effects and interactions.

ASSESSING SOIL HEALTH

Soil health is broader than the nutrient status measured immediately after harvest. It concerns the soil's continuing ability to support plants and biological processes while performing functions such as water storage and nutrient cycling. An agricultural assessment might include physical indicators such as aggregation or water infiltration; chemical indicators such as pH, organic carbon, and available nutrients; and biological indicators such as microbial biomass, enzyme activity, or the effectiveness of beneficial root associations. No single measurement captures the whole concept.

A rise in post-harvest available phosphorus is useful information, but its meaning requires context. It may reflect a greater amount mobilized, a lower amount taken up by plants, a

fertilizer application, or a combination of processes. Likewise, a high yield in one season demonstrates crop productivity under that season's conditions; it does not alone demonstrate a lasting improvement in soil health. To assess sustainability, researchers should ideally measure soil before treatment and after harvest, examine more than one season, and consider the following crop.

Organic amendments may influence several indicators at once. They can supply nutrients while adding carbon-containing material to soil. Their composition varies, however, and the quantity and quality applied determine the likely effect. In a fenugreek study comparing manures and *Rhizobium*, Aishwath and colleagues found that farmyard manure produced the highest yield among the inputs examined and that soil organic carbon was higher with sheep manure and farmyard manure. Their findings warn against treating all materials labelled "organic" as nutritionally equivalent. A commercially available vermicompost, for example, should be assessed on its actual composition and field performance.

Microbial inoculants can affect soil processes without necessarily increasing soil organic carbon. *Rhizobia* may contribute to nitrogen inputs through fixation; PSB can participate in phosphorus cycling. Their populations, however, may change after the crop is harvested, and a single application does not guarantee a permanent increase in a soil's microbial diversity or fertility. It would be inaccurate to infer enduring soil improvement solely from the presence of a beneficial bacterium in the applied product. Long-term soil claims require repeated measurements and attention to the whole management system.

Patel and colleagues' organic-farming experiment at Sardarkrushinagar is relevant because it evaluated yield, nutrient uptake, economics, and post-harvest soil characteristics. The combination of castor cake supplying part of the recommended nitrogen with *Rhizobium* and PSB inoculation performed well in their comparison and was associated with higher soil organic carbon and available nutrients than several other treatments. The result is specific to the treatments and loamy sand soil studied. It supports the value of examining microbial inoculation within an organic nutrient system, while leaving open how the same combination would perform in soils with different phosphorus chemistry or sources of organic material.

A further question is whether a fenugreek treatment benefits the following crop. Choudhary and colleagues studied integrated nutrient management in a fenugreek–fodder pearl millet

sequence at Jobner. Their work examined not only fenugreek growth, yield, nodulation, and nutrient uptake but also residual effects within the cropping system. This design is valuable because the environmental and economic consequences of fertilization often extend beyond the season in which an input is applied. A treatment that leaves useful nutrients or improves the next crop may have value that a single-season seed-yield comparison miss.

INTEGRATED NUTRIENT MANAGEMENT IN FENUGREEK

Integrated nutrient management begins with the recognition that different nutrient sources perform different functions. Mineral fertilizers can correct a measured shortage promptly. Manures can contribute nutrients and organic material. Rhizobia may supply biologically fixed nitrogen, and PSB may increase access to certain soil phosphorus pools. Their combination is most useful when each component addresses a real limitation without duplicating inputs unnecessarily.

The Jobner fenugreek–pearl millet experiment found that a treatment combining poultry manure and inorganic nitrogen at specified shares produced strong fenugreek growth, nodulation, seed yield, and nutrient uptake within its comparison. Another treatment involving vermicompost and inorganic inputs produced the highest net returns per rupee invested for the cropping system. These distinctions matter. The treatment producing the greatest biological response need not be the treatment with the strongest economic result, and the preferred option may change with manure prices, transport, labour, or the value of the following crop.

In the Udaipur experiment, dual Rhizobium and PSB inoculation performed better than the single inoculants or uninoculated treatment for reported yield and soil nutrient outcomes. At the same time, the higher fertilizer level studied was associated with strong growth and yield responses. This is evidence for evaluating microbial inoculation alongside a sensible fertilizer program. To establish partial replacement, a future trial would need to compare, for example, a full fertilizer treatment with a lower fertilizer treatment plus inoculation and test whether differences in yield, economics, and soil outcomes were acceptable.

At Sardarkrushinagar, Patel and colleagues found that castor cake combined with both Rhizobium and PSB inoculation improved yield attributes, nutrient content and uptake, and selected soil measures within an organic production experiment. Their design shows that microbial inoculation can be relevant even when readily soluble chemical fertilizers are absent

from a treatment. But castor cake is itself a substantial nutrient input. The result should thus be understood as the performance of a complete organic–microbial management combination, not as evidence that bacteria alone supplied every nutrient removed in the crop.

These studies also caution against transplanting a treatment formula unchanged from one region to another. A field's existing nutrient status, access to good-quality manure, water supply, cultivar, and intended product influence the most useful combination. Sustainable management starts with a soil assessment and a production objective. The role of bio-fertilizers can then be tested within an input plan designed for that field rather than added as a general-purpose substitute.

ECONOMIC AND PRACTICAL CONSIDERATIONS

A bio-fertilizer may be inexpensive per package yet costly to a grower if it produces inconsistent results or requires additional handling without a dependable return. Economic evaluation should include product purchase, transport, storage, seed-treatment labour, fertilizer costs, and the value of the final harvest. It should also consider whether an input affects the next crop or reduces a later management cost. Field trials in fenugreek have reported differences in net returns and benefit–cost ratios across nutrient treatments, demonstrating that the most profitable option cannot be inferred from plant height alone.

Product quality is central to the practical result. A living microbial preparation must contain the intended organism in adequate viable numbers when the farmer applies it. Storage conditions and the age of the product can alter survival. If different organisms are combined, they must remain compatible in the formulation and during application. Reviews of phosphate-solubilizing bio-fertilizers identify formulation and quality control as major steps between promising laboratory research and reliable agricultural use.

The method of application must also suit the crop. Seed inoculation can place microorganisms near emerging roots, while soil application may distribute them more broadly. Whatever method is selected, clear instructions and careful handling are needed. An agronomic recommendation should specify the tested product, strain or strains, application method, and conditions under which the result was observed. It should not simply advise growers to “use bio-fertilizer” without identifying what biological function and field limitation the product is intended to address.

LIMITS OF THE EXISTING EVIDENCE

Positive studies are informative, but their findings have boundaries. Many experiments test particular strains on particular soils during one or two seasons. A treatment response may reflect a low initial nutrient status, unusually favourable moisture, or a cultivar well matched to the tested organism. Results need replication in fields representing the conditions for which a recommendation is intended.

The measured outcome also determines what can be concluded. Better seed germination does not prove a rise in seed yield. Greater microbial activity in soil does not by itself establish a higher marketable harvest. Higher available nutrients immediately after harvest do not prove that the nutrient balance will remain favourable after repeated cropping. An article evaluating sustainability must keep these measures distinct even when they point in the same encouraging direction.

Attribution presents another limitation. When a treatment includes manure, Rhizobium, PSB, and mineral fertilizer, an improved yield belongs to the combination unless the experimental design permits separate effects to be estimated. Comparing the combination only with an untreated control cannot show how much of the result arose from each component. Likewise, a PSB strain may have several plant-growth-promoting traits. Researchers should avoid assigning all its observed effects to phosphorus solubilization without supporting measurements.

Finally, the phrase “chemical-free” should not be used as a shortcut for sustainability. Crops remove nutrients from fields, and soils differ in their ability to replace those nutrients. In one setting, an effective microbial and organic management program may maintain a worthwhile yield with a reduced mineral fertilizer rate. In another, omitting a needed nutrient may reduce production or deplete soil reserves. Sustainable practice requires evidence of productive crops and a defensible longer-term nutrient balance.

INTERNATIONAL PERSPECTIVES

International research provides a wider framework for interpreting fenugreek experiments. A synthesis of grain-legume studies under Ghanaian conditions examined responses to rhizobial inoculation and phosphorus supplementation. Its findings reinforce the importance of the

interaction among crop genotype, microbial inoculant, nutrient input, and local soil. The lesson for fenugreek is methodological: researchers should test combinations under the conditions in which they will be used, rather than assume a single microbial product will produce the same response across regions.

Reviews drawing on work from several countries show that phosphate-solubilizing microorganisms differ widely in their mechanisms and effectiveness. Soil pH, the type of phosphorus compound, moisture, and competition with resident microorganisms can influence whether a laboratory trait becomes a measurable field benefit. Research on mineral-weathering bacteria and rhizosphere interactions therefore supports careful strain selection and local validation. It also encourages attention to interactions among bacteria, roots, and other microorganisms rather than treating the inoculant as acting independently of the soil community.

Fenugreek research beyond India contributes different production settings. Work on bio-priming and plant-growth-promoting bacteria has examined nutrient absorption and dry matter in fenugreek. Research on *Bacillus subtilis* ER-08 explored growth and nutrient responses under drought and salinity. These studies cannot replace direct trials of the specific *Rhizobium* and PSB products proposed for an Indian field, but they identify conditions and outcomes worth measuring. Drought tolerance, for example, could matter greatly in a region where the crop regularly experiences water limitation.

The international perspective also changes how sustainability is judged. A high-yield treatment may be attractive where land is scarce, while a lower-input treatment may be preferred where cash costs or access to fertilizer present the greater constraint. Both cases require transparent evidence on yield, costs, nutrient use, and soil condition. Researchers can make their work more transferable by reporting microbial strain identity, inoculant viability, soil properties, weather, fertilizer rates, and the precise harvest measured. Negative findings are valuable as well: they indicate where a biological practice does not solve the limitation present.

A FRAMEWORK FOR FUTURE FENUGREEK FIELD TRIALS

The next stage of research should ask a precise replacement question. Investigators might test whether inoculation allows a specified reduction in mineral nitrogen or phosphorus while maintaining seed yield and selected soil indicators. A different trial might test whether bio-

fertilizers improve leaf yield under an organic system. These are separate objectives and should have separate treatment designs.

A basic experiment would compare an uninoculated treatment, Rhizobium alone, PSB alone, and their combination. These microbial treatments could then be evaluated at carefully chosen fertilizer levels, including a locally relevant full-rate comparison and one or more reduced-rate treatments. Where organic materials are studied, their nutrient composition and application quantities should be reported. This design makes it possible to ask whether the combined inoculant provides an additional benefit, whether a reduced mineral rate performs adequately, and whether manure changes either result.

Before sowing, investigators should measure relevant soil properties, including pH, organic carbon, and available nutrients. They should confirm the identity and viability of inoculant strains and record how products are stored and applied. Plots should be randomized and replicated, and the trial should be repeated in more than one season or location if broad recommendations are intended. Weather and irrigation should be documented because microbial establishment and nutrient acquisition depend partly on moisture.

Measurements should follow the proposed mechanism. Emergence and early growth indicate whether seed treatment assists establishment. Nodule number, size, and effectiveness help assess the rhizobial association. Plant nitrogen and phosphorus content and total uptake show whether nutrient acquisition changes. Leaf yield or seed-yield components establish the agricultural outcome. Soil indicators taken after harvest and, where possible, performance of the following crop help test the soil-health claim.

Economic analysis should use the same level of care as biological analysis. The most productive treatment may not be the most profitable once inoculant, manure, transport, and labour costs are included. Researchers should report variation as well as treatment averages and identify which comparisons are statistically supported. A recommendation becomes persuasive when growers can see the conditions, costs, and likely range of outcomes associated with it.

CONCLUSION

Bio-fertilizers offer a credible means of improving nutrient acquisition in fenugreek, but their role as an alternative to chemical fertilizers depends on the meaning of replacement and the conditions in which it is tested. Compatible rhizobia can support biological nitrogen fixation, and suitable PSB can help mobilize some poorly available phosphorus. Fenugreek studies report gains in growth, yield, or nutrient uptake from selected microbial treatments, particularly combined inoculation or integration with organic nutrient sources. Other trials show a substantial benefit from mineral fertilizer, and one Jobner experiment recorded its highest seed yield and returns with inorganic nitrogen alone. The literature therefore supports a conditional conclusion rather than a universal substitution rule.

Sustainable cultivation requires attention to the harvested crop and the soil that remains after harvest. Bio-fertilizers are most promising when the strains are viable and suited to fenugreek, the field presents a nutrient limitation they can address, and their effects are evaluated alongside soil testing and appropriate organic or mineral nutrient supply. Claims of reduced fertilizer requirements should be based on trials that directly compare reduced and full nutrient rates. With that evidence, microbial inoculation can become a practical part of efficient fenugreek management and longer-term soil stewardship.

FUTURE SCOPE

Future research should identify fenugreek-compatible rhizobia and PSB adapted to distinct soil environments, including the loamy sands and other soils used for seed-spice production. Strains should be screened for their intended functions and for compatibility within a shared formulation. Longer shelf life, reliable seed-coating methods, and field survival deserve as much attention as laboratory phosphate-solubilization measurements.

Multi-season trials should evaluate leaf and seed production separately and measure nitrogen fixation, phosphorus uptake, yield, soil organic carbon, nutrient balance, and subsequent crop performance. Experiments should directly test whether particular mineral fertilizer rates can be reduced without an unacceptable loss of yield or profit. Publishing both favourable and unfavourable results will help identify where bio-fertilizers are dependable, where integrated treatments work best, and where conventional nutrient inputs remain necessary.

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