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Status of bacterial inoculants for micronutrients solubilization in perspective of Seed spices crops: a review

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Abstract

Bacterial inoculants play a crucial role in improving soil fertility and enhancing plant nutrition by facilitating the solubilization of essential micronutrients in agricultural ecosystems. Their ability to mobilize micronutrients is crucial for optimizing both the yield and quality of seed spice crops. This review provides a comprehensive assessment of bacterial inoculants and their efficacy in solubilizing key micronutrients such as zinc, iron, manganese, and copper, with a particular focus on seed spice cultivation. It highlights the mechanisms employed by various bacterial species to enhance micronutrient availability and discusses their potential applications in sustainable agriculture. Given the small seed size of spice crops, germination remains a significant challenge, adding complexity to their cultivation. The review also examines the factors that influence the effectiveness of bacterial inoculants, including soil characteristics, environmental conditions, and agronomic management practices. Additionally, it addresses the challenges and limitations associated with their application in seed spice production and suggests potential strategies for overcoming these constraints. Emphasizing the need for continued research and innovation, this review underscores the significance of bacterial inoculants in promoting sustainable micronutrient solubilization for improved seed spice productivity.

Keywords: Bacterial inoculants, micronutrient solubilization, Seed spices crops, plant nutrition, sustainable agriculture.

1. Seed spices crops: An overview

1.1 Seed spices crops and the Role of Biopriming in Micronutrient Solubilization

Seed spices crops comprise a diverse group of plants cultivated primarily for their seeds, which are widely used as spices and flavoring agents in culinary applications. These crops thrive in warm climates with well-drained soils and include economically significant species such as cumin (*Cuminum cyminum*), coriander (*Coriandrum sativum*), fennel (*Foeniculum vulgare*), fenugreek (*Trigonella*

foenum-graecum), ajwain (*Trachyspermum ammi*), nigella (*Nigella sativa*), and dill (*Anethum graveolens*). Beyond their culinary value, Seed spices crops possess distinctive aromatic properties and offer various health benefits due to their rich composition of vitamins, minerals, and bioactive compounds. They exhibit antimicrobial, anti-inflammatory, and antioxidant properties, contributing to their widespread use in traditional medicine. The seed spice industry plays a crucial role in global trade, significantly impacting agricultural economies and providing livelihoods to millions of farmers and workers worldwide (Lal et al., 2009; Mishra et al., 2025).

Despite their economic and nutritional significance, seed spice cultivation faces several agronomic challenges, particularly nutrient deficiencies in the soil, which limit crop productivity and quality. Micronutrients play essential roles in plant biochemical and physiological processes, yet their limited availability in the soil often constrains optimal growth and development. Enhancing micronutrient solubilization is, therefore, a critical aspect of sustainable seed spice production.

Biopriming has emerged as an innovative and eco-friendly seed treatment strategy aimed at improving seed germination, seedling vigor, and overall plant performance. This technique involves coating seeds with beneficial microorganisms, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal

fungi, before sowing. These microorganisms establish beneficial interactions with seeds and seedlings, enhancing nutrient solubilization, synthesizing growth-promoting compounds, and inducing systemic resistance against pathogens. The fundamental mechanism of biopriming lies in its ability to improve nutrient uptake and utilization efficiency through microbial activity. PGPR and mycorrhizal fungi secrete organic acids and enzymes that mobilize essential micronutrients, transforming them from insoluble to bioavailable forms. Additionally, these microorganisms stimulate root development and modify root architecture, increasing the plant's capacity for nutrient absorption (Figure 1).

Therefore, this review aims to provide an in-depth analysis of biopriming principles, its effectiveness in enhancing micronutrient availability, and its potential applications in seed spice production. Furthermore, it explores current research trends, existing challenges, and future prospects, emphasizing the need for continued scientific advancements to optimize biopriming strategies for sustainable seed spice cultivation (Figure 2).

1.2 Impact of Micronutrient Supplementation and Bacterial Inoculation on Seed Spice Cultivation

The widespread adoption of intensive cropping systems, which involve cultivating multiple crops on the same land, has led to a depletion of essential micronutrients in Indian soils. As a result farmers are

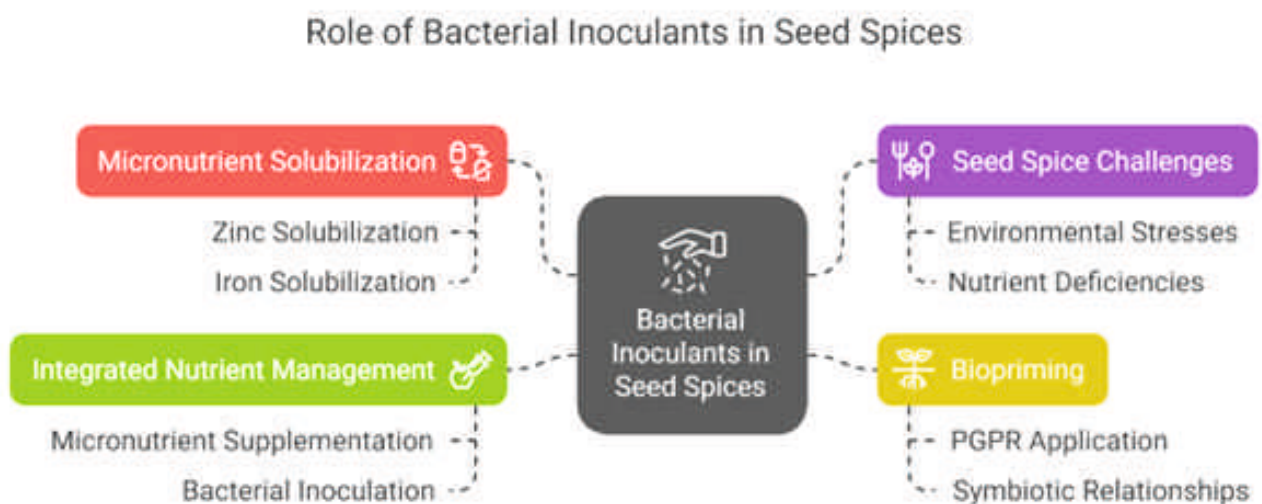


Figure 1: Role of bacterial inoculants in Seed spices crops crops

Benefits of seed biopriming

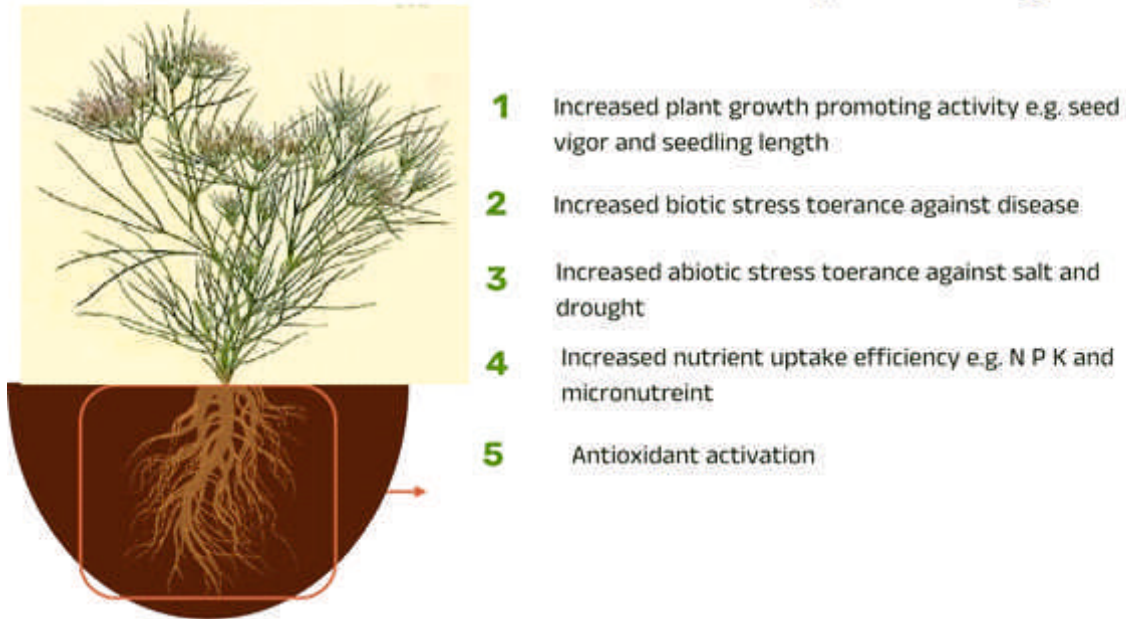


Figure 2: Benefits of seed biopriming

increasingly recommended to supplement seed spice crops with external micronutrient applications. However, there remains a limited understanding of the effects of integrated nutrient management, particularly the combined influence of bacterial inoculation and micronutrient supplementation, on seed spice productivity and quality.

Several studies conducted both in India and internationally have highlighted the critical role of micronutrients such as zinc, sulfur, iron, and boron in seed spice cultivation. For instance, the recorded average uptake of essential micronutrients by cumin (*Cuminum cyminum*) includes 439.8 g/ha of iron, 201.8 g/ha of manganese, 107.6 g/ha of copper, 22.2 g/ha of zinc, and 37.4 g/ha of boron. Furthermore, research has demonstrated that different methods of micronutrient application significantly impact plant growth and yield compared to untreated controls. For example, soil application of iron at 10 kg/ha has been found to enhance fennel (*Foeniculum vulgare*) growth and yield, similar to the effects observed with manganese application at the same rate.

Studies investigating the role of bacterial inoculation in seed spice cultivation have also shown promising results. Mishra et al. (2016) reported a positive

correlation between bacterial inoculation, essential oil content, and yield in fennel under semi-arid conditions, which was attributed to phosphate-solubilizing bacterial strains. Similarly, in coriander (*Coriandrum sativum*) seedlings, the highest seedling vigor index was recorded with the bacterial isolate *Bacillus aerophilus* Cor-15 (1178.50), followed by *B. megaterium* (1125.20), whereas the control exhibited the lowest vigor (Mishra et al., 2017).

Additionally, seed treatment with native *Bacillus* species has shown a significant impact on cumin growth and yield. Inoculation resulted in a substantial increase in secondary branch formation, with treated plants exhibiting a higher number of branches than the control. The highest dry weight per plant (5.26 g/plant) was recorded in the treatment with *B. subtilis* + *B. megaterium* + *B. sp.*, followed by *B. megaterium* + *B. sp.* (4.85 g/plant). Moreover, the maximum seed yield (451.6 kg/ha) was observed in treatment group T6 (*B. subtilis* + *B. megaterium* + *B. sp.*), whereas the control group had the lowest yield (353.70 kg/ha). Variations in essential oil content were also noted among treatment groups, with the highest content (4.05%) recorded in T4 (*B. subtilis* + *B. megaterium*), while the lowest (3.28%) was observed in T5 (*B. megaterium* + *B. sp.*)

(Mishra et al., 2019).

These findings underscore the significance of integrating bacterial inoculants with micronutrient supplementation to enhance seed spice growth, yield, and essential oil content. Further research is necessary to optimize these biofertilization strategies for sustainable and high-yielding seed spice production (Figure 4).

1.3 Impact of Biofertilizers, Organic Amendments, and Micronutrients on Growth and Yield of Seed

spices crops

Significant improvements in growth and yield parameters were observed with the application of integrated nutrient management strategies. The treatment involving the recommended dose of farmyard manure (RDFYM), 75% recommended dose of nitrogen (RDN), recommended dose of phosphorus and potassium (RDPK), along with *Azospirillum* at 5 kg ha⁻¹ and phosphate-solubilizing bacteria (PSB) at 3 kg ha⁻¹ (T6) resulted in the highest values for plant height

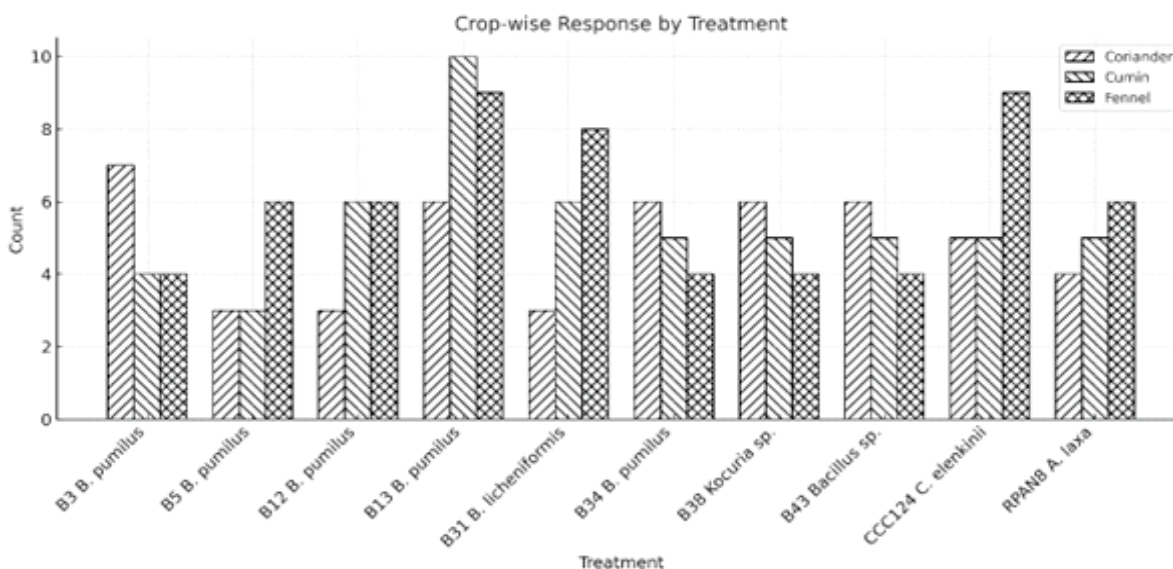


Figure 3: Comparative performance of microbial inoculation crop-wise response (Coriander, Cumin, and Fennel) (Kumar et al., 2013)

Different growth-promoting activities of PGPR on the seed spices

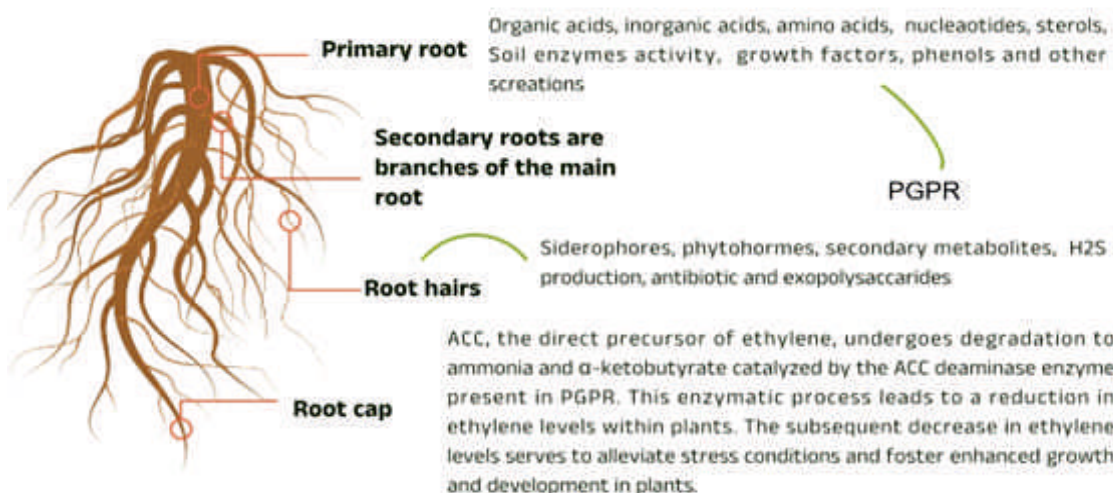


Figure 4: Different growth-promoting activities of PGPR on the Seed spices crops

(209.97 cm), number of primary and secondary branches (16.43 and 7.50, respectively), number of umbels per plant (29.24), umbellets per umbel (23.68), seeds per umbellet (35.07), and 1000-seed weight (7.35 g) (Kusum et al., 2019). Similarly, Godara et al. (2014) reported enhanced growth and yield attributes in fennel when the recommended dose of fertilizers (RDF) was applied through chemical fertilization, followed by integrated nutrient management. The observed improvements in plant height could be attributed to the production of phytohormones, which promote root proliferation and enhance nutrient uptake (Figure 5).

Studies on black pepper (*Piper nigrum*) have also demonstrated the benefits of biofertilizers and organic amendments in improving plant vigor. The application of phosphorus-solubilizing bacteria (PSB) at 5 g, *Azospirillum* at 5 g, humic acid (0.2%), and fish extract (0.5%) was found to be the most effective combination for producing black pepper rooted cuttings with superior vegetative growth characteristics, including increased plant height, number of leaves, root number, root length, and leaf area. This approach offers a promising strategy for commercial production of robust black pepper rooted cuttings (Aswathy et al., 2018).

Further investigations on ajwain (*Trachyspermum ammi*) assessed the effects of organic manures, plant growth-promoting rhizobacteria (PGPR), and micronutrient applications on seed yield and quality. Organic amendments, including farmyard manure (FYM) and vermicompost (VC), were applied at 50% and 75% RDN as basal doses. PGPR strains such as *Azospirillum lipoferum*, *Bacillus megaterium*, and *Frateruria aurantia* were utilized for seed priming, while micronutrients, specifically ZnSO₄ and FeSO₄, were applied as foliar sprays at 0.5% at three critical growth stages: pre-flowering, mid flowering, and grain formation. The highest values for umbels per plant, umbellets per umbel, fruits per umbellet, seed yield per plant, seed yield per hectare, straw yield, biological yield, 1000-seed weight, and essential oil yield were recorded with the application of 50% RDN through VC. These results were statistically comparable to those obtained with 50% RDN through FYM, seed priming with *Azospirillum*, and foliar zinc application. Additionally, the highest essential oil content, fixed oil content, and thymol concentration were observed in

treatments involving 50% RDN through VC, *Azospirillum* seed priming, and foliar zinc application individually. The highest benefit-cost ratio (BCR) of 3.33 was achieved with the combined application of 50% RDN through FYM, seed priming with *Azospirillum*, and foliar zinc spray at 0.5% (Thanuja et al., 2021).

These findings emphasize the potential of integrating biofertilizers, organic amendments, and micronutrient applications to optimize growth, yield, and quality parameters in seed spice production while enhancing economic returns for farmers.

Microorganisms require a variety of nutrients for their growth and metabolic processes, among which zinc plays a crucial role as a cofactor and metal activator in numerous enzyme systems. The significance of zinc in the nutrition and physiology of both eukaryotic and prokaryotic organisms has been extensively studied, particularly its involvement in enzymatic activity. Zinc deficiency in fungi and bacteria has been associated with impaired pigment formation, affecting compounds such as melanin, chrisogenin, prodigiosin, and subtilin (Chernavina, 1970). Some fungal species exhibit remarkable zinc-solubilizing capabilities, enabling them to tolerate high zinc concentrations. *Aspergillus niger*, for instance, has been observed to grow in environments containing up to 1000 mg Zn, making it a valuable bioindicator for quantifying zinc availability in soils with low zinc content (2 mg/kg available Zn) (Bullen & Kemila, 1997).

Zinc is an essential micronutrient for both plants and microorganisms, functioning as a key component in various enzymatic reactions. Several bacterial enzymes incorporate zinc either in their active sites or in structurally significant regions. Bacteria contribute to metal immobilization through multiple mechanisms, including precipitation and adsorption. In anoxic conditions, sulfate-reducing bacteria facilitate the formation of highly insoluble metal sulfide precipitates, thereby playing a role in zinc bioavailability and biogeochemical cycling (Gadd, 1996; White et al., 1997).

The zinc-solubilizing potential of various bacterial genera has been widely explored. Hutchins et al. (1986) reported that *Thiobacillus thiooxidans*, *Thiobacillus ferrooxidans*, and facultative thermophilic

iron oxidizers are capable of solubilizing zinc from sulfide ore (sphalerite). The application of exogenous soluble zinc sources, akin to fertilizer supplementation in agriculture, has been recommended for various crops. However, approximately 96–99% of applied zinc undergoes transformation into unavailable forms. Inoculating soil with bacterial strains capable of solubilizing zinc has been suggested as a viable strategy to restore its bioavailability (Saravanan et al., 2003), particularly in alkaline and calcareous soils where zinc availability is a limiting factor for crop productivity.

Bapiri et al. (2012) assessed the zinc-solubilizing efficiency of *Pseudomonas fluorescens* using zinc oxide (ZnO), zinc carbonate (ZnCO₃), and zinc sulfide (ZnS) in both plate and broth assays. Forty bacterial strains were tested with 0.1% of each zinc compound, with six replications per treatment. The colony and halo diameters were recorded after 48 hours of incubation. In broth assays, the solubilizing potential of 40 bacterial strains was evaluated using ZnO and ZnCO₃. Soluble zinc concentrations and pH shifts were measured after five days of incubation. Results indicated that only eight out of the 40 strains formed a clearing zone in the plate assay. The halo diameters, halo-to-colony ratios, and dissolution areas for ZnO and ZnCO₃ varied as follows: 0.60–1.32 cm, 1.20–2.64, and 0.95–2.60 cm² for ZnO; and 0.13–1.70 cm, 0.27–2.99, and 0.31–4.10 cm² for ZnCO₃, respectively. No halo formation was observed with ZnS. In the broth assay, the soluble Zn concentration ranged from 28–625 mg/L for ZnO and 247–753 mg/L for ZnCO₃. The pH decreased from 7.0–7.2 to 3.90–6.50 in ZnO treatments and from 7.0–7.2 to 3.5–6.3 in ZnCO₃ treatments after five days of inoculation at 28°C.

The zinc-solubilizing ability of *Bacillus* sp. and *Pseudomonas* sp. was further evaluated using ZnO, ZnS (sphalerite), and ZnCO₃ in both plate and broth assays. In contrast, the *Pseudomonas* strain ZSB-S-2 demonstrated greater solubilization potential for ZnO, with a 3.30 cm clearing zone, 20.43 cm² dissolution area in the plate assay, and 16.40 mg/kg zinc concentration in the broth assay over the same period. The ZSB-S-4 strain of *Pseudomonas* exhibited the highest solubilization activity in ZnCO₃, with a dissolution zone of 6.20 cm, a dissolution area of 13.40

cm² in the plate assay, and 13.40 mg/kg of zinc in the broth assay. The variation in solubilization potential among bacterial cultures was attributed to organic acid production, as evidenced by pH reductions from 7.0–7.3 to 4.8–6.5 within 15 days of inoculation. The zinc tolerance limit for ZSB-O-1 and ZSB-S-2 was determined to be up to 100 mg/kg in in vitro broth assays (Saravanan et al., 2003).

These findings highlight the potential of zinc-solubilizing bacteria in enhancing zinc bioavailability, which can be leveraged to improve nutrient acquisition in plants, particularly in soils with limited zinc availability. The ability of microbial strains to solubilize and mobilize zinc provides a promising avenue for sustainable agricultural practices, reducing dependency on synthetic fertilizers while improving plant growth and productivity.

2. Factors Influencing Microbial Dynamics in the Rhizosphere

Extensive research has been conducted on the application of various microorganisms as inoculants for multiple purposes, including plant disease suppression, growth promotion by plant growth-promoting rhizobacteria (PGPR), and bioremediation. One of the most notable applications of beneficial soil bacteria is the inoculation of legumes with *Rhizobium* and *Bradyrhizobium* species, facilitating biological nitrogen fixation. Certain crops can fulfill their nitrogen requirements almost entirely through this symbiotic process, as the host plant selectively recruits the bacteria and forms specialized root nodules that optimize nitrogen fixation. Despite this well-established symbiosis, inoculation failures occasionally occur due to various environmental and biological factors. A persistent challenge in microbial inoculation is the unpredictable effectiveness in pest control or plant growth enhancement, which can result from multiple interacting factors.

Microbial establishment in the rhizosphere is influenced by several constraints. When introduced into the soil at low concentrations, bacterial inoculants often struggle to establish themselves due to competition with native microbial communities. Additionally, biotic factors such as microbial toxins, predation, and viral lysis further hinder the survival of introduced microbes. Some of the key biotic constraints

include:

- **Microbially produced toxins** – Certain native soil microbes produce antimicrobial compounds that inhibit introduced bacteria.
- **Predatory protozoa** – Protozoan grazing can significantly reduce bacterial populations.
- **Lysis by bacteriophages** – Bacterial viruses (bacteriophages) specifically target and lyse bacterial cells.
- **Lysis by *Bdellovibrio bacteriovorus*** – This predatory bacterium preys on other bacterial species.
- **Lysis by microbial enzymes** – Native microbes secrete hydrolytic enzymes that degrade foreign bacterial cells.
- **Inability of the introduced microbe to compete** – Introduced microbes may lack competitive traits necessary for survival in the rhizosphere.

In addition to biotic factors, abiotic environmental conditions often contribute to the decline of introduced microbial populations. Soil physicochemical properties,

such as pH extremes, metal toxicity, and temperature fluctuations, can negatively affect microbial establishment. Some of the key abiotic constraints include:

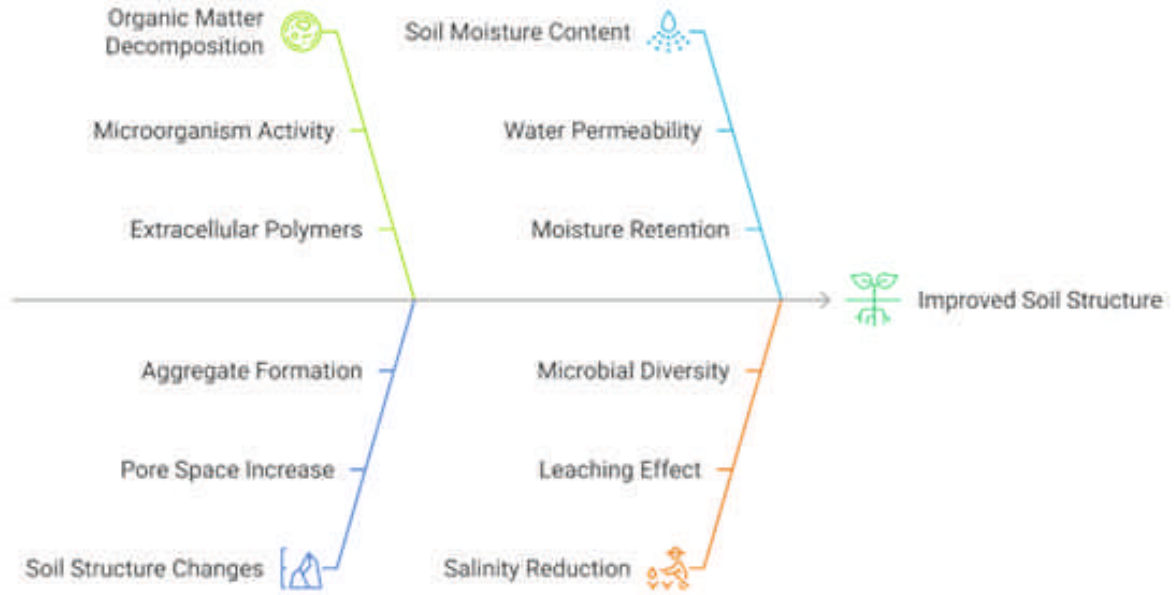
- **Extreme soil pH (high or low values)** – Affects microbial viability and enzymatic activity.
- **High concentrations of metals (e.g., Mn, Al, etc.)** – Some metals can be toxic to microbial communities.
- **Extreme temperature fluctuations** – Affects microbial metabolic activity and survival.
- **Soil salinity and sodicity** – These edaphic factors can inhibit microbial colonization and function.

Soil microbial communities are inherently stable and well-adapted to the prevailing environmental conditions. Minor disturbances typically do not disrupt this equilibrium. However, the combined effects of biotic and abiotic factors often impede the success of microbial inoculants in agricultural applications. Due to these inconsistencies, the adoption of microbial-based



Figure 5: Exploring bacterial inoculants in Seed spices crops

Enhancing Soil Structure with Bioinoculants



Biofertilizer Enhances Soil Microbial Activity

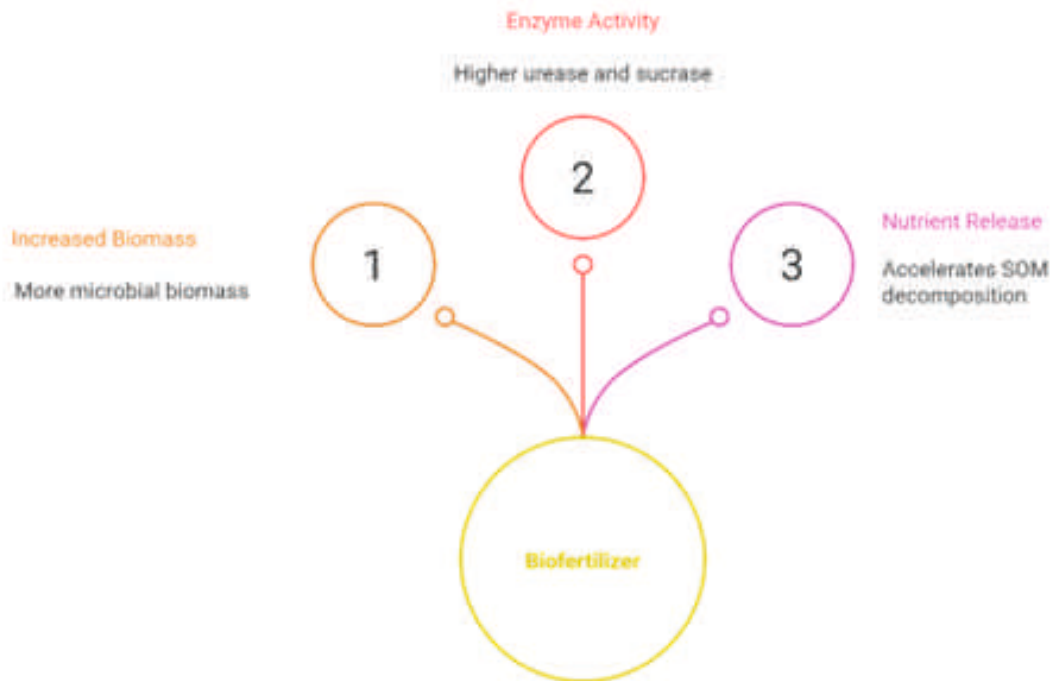


Figure 6: Influence of Soil Physicochemical Properties on Inoculant Efficacy

alternatives remains a challenge for many farmers.

2.1 Integrating Microbial Inoculants with Nutrient Management in Seed spices crops

Like other annual crops, seed spice crops respond positively to the external application of macro- and micronutrients through soil amendments and foliar sprays. Historically, plant nutrition research has emphasized optimizing chemical fertilizer use to achieve immediate yield benefits, often at the expense of long-term soil fertility. In contrast, sustainable agricultural practices now advocate for the integration of organic amendments, such as vermicompost (VC) and farmyard manure (FYM), in combination with biofertilizers and PGPRs to enhance productivity while maintaining soil health. However, limited research has been conducted on the combined application of biofertilizers and micronutrients in seed spice production systems.

To maintain soil fertility and environmental sustainability, inorganic fertilizers should be supplemented with biofertilizers. Iron deficiency is particularly problematic in high-pH soils (above 7.5), which are predominant in the seed spice-growing regions of Rajasthan and Gujarat. Additionally, the roles of sulfur, zinc, copper, and boron in plant metabolism are well-established. However, the nutrient status of these elements has declined due to intensive cropping practices and inadequate recycling of crop residues.

2.2 Microbial Interactions in the Rhizosphere and Their Role in Nutrient Cycling

Plant growth-promoting rhizobacteria (PGPR) colonize the rhizosphere and occupy approximately 5–17% of the total root surface (Gray & Smith, 2005). The most extensively studied PGPR genera include *Rhizobium*, *Pseudomonas*, *Bacillus*, and *Azospirillum*, which have been shown to enhance seed germination, seedling emergence, and overall plant growth (Ahmad et al., 2008). The interactions between plant roots and soil microbiota play a critical role in nutrient acquisition and plant health (Richardson et al., 2009).

Soil microorganisms contribute to plant nutrition through multiple mechanisms, including:

- **Synthesis of plant growth hormones (auxins and gibberellins)** – Promotes root and shoot development.

- **Biological nitrogen fixation** – Enhances nitrogen availability for plant uptake.
- **Phosphate solubilization** – Converts insoluble inorganic phosphate into plant-available forms.
- **Organic phosphate mineralization** – Releases phosphorus from organic matter, making it accessible to plants.

These microbial processes play a fundamental role in sustaining soil fertility and plant health, offering a promising approach to reducing dependency on synthetic fertilizers while improving crop productivity.

3. Future Prospects

Future research on bacterial inoculants for micronutrient solubilization in Seed spices crops should prioritize field-level validation of promising strains across varied agro-climatic zones to assess consistency and adaptability. Integrating molecular tools such as genomics and transcriptomics will help uncover gene-level mechanisms involved in micronutrient mobilization, such as siderophore and organic acid biosynthesis. There is also a pressing need to develop robust bioformulations with enhanced shelf-life and effective delivery systems like seed coating or encapsulation. Understanding soil–plant–microbe interactions, especially under different soil types and stress conditions (e.g., salinity, drought), will be key to improving field efficacy. Exploring microbial consortia could offer synergistic effects on nutrient solubilization and stress tolerance. Additionally, microbial inoculants should be evaluated for their role in climate-resilient agriculture and integrated into sustainable and export-oriented production systems. Finally, policy support, farmer training, and commercial scalability are essential to ensure widespread adoption and long-term impact on seed spice productivity and quality.

Conclusion

Extensive research on the integration of beneficial bacterial inoculations and soil-applied micronutrients in seed spice cultivation—particularly for ajwain, coriander, cumin, and fennel—can facilitate the optimization of nutrient management strategies. This approach aims to enhance crop yields while maintaining long-term soil health. To maximize the efficacy of microbial inoculants, it is essential to prioritize the selection of native microbial isolates with

strong rhizosphere competence. Rather than relying solely on single-strain inoculants, the development of synthetic microbial communities through microbiome studies of dominant cropping systems presents a more effective strategy for sustainable agriculture.

Microorganisms play a crucial role in nutrient cycling and overall ecosystem stability. However, the full potential of microbial inoculants in improving micronutrient bioavailability remains an ongoing area of research. Continued efforts are required to refine microbial applications and develop more effective strategies for harnessing their benefits in agricultural systems.

Conflict of interest

The authors declare that the research was conducted beyond any commercial or financial affairs that could be taken as a potential conflict of interest.

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