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Eco-friendly strategies for spice production through microbial inoculants

The growing emphasis on residue-free spices and environmentally sustainable agriculture has driven the need for eco-friendly alternatives to conventional chemical inputs. This study underscores the crucial role of microbial inoculants in spice cultivation, functioning as biofertilizers, biopesticides, and biocontrol agents. Beneficial microbes such as *Trichoderma* spp., Bacillus *licheniformis, Pochonia chlamydosporia,* and various PGPR strains have proven effective in suppressing diseases, enhancing nutrient availability, and promoting plant growth in crops like ginger, turmeric, cardamom, and black pepper. Integrating these microbial tools not only boosts crop productivity and resilience but also ensures compliance with stringent international standards, thereby supporting sustainable and export-oriented spice production.

HARNESSING natural resources, particularly beneficial microorganisms, offers a promising and sustainable strategy to enhance agricultural productivity and food quality. Modern agricultural systems are increasingly reliant on chemical inputs, which have led to significant challenges such as food contamination, the emergence of resistant weed and pathogen populations, and the degradation of soil and water resources. As a sustainable alternative, microbial inoculants–functioning as biofertilizers, biopesticides, bioherbicides, and biocontrol agents–offer multifaceted benefits. These microorganisms play a pivotal role, especially in organic farming systems, by improving nutrient availability, suppressing pests and diseases, and maintaining soil health. Their application contributes significantly to sustaining soil fertility and ecosystem functions, ultimately promoting environmentally sound and resilient agricultural practices.

Beneficial microbes in plant disease management

Trichoderma species, owing to their ubiquitous distribution and ecological dominance, have emerged as one of the most promising microorganisms in the field of biological control, plant growth promotion, and disease suppression. These fungi are characterized by minimal nutritional requirements and possess the ability to utilize complex substrates such as cellulose and chitin as carbon sources. Strains of *Trichoderma* exhibit multiple mechanisms of antagonism against plant pathogenic fungi. These include:

- Antibiosis, through the synthesis of a broad spectrum of secondary metabolites with antimicrobial properties.
- Competition, where they effectively outcompete pathogens for nutrients and space.
- Mycoparasitism, involving the secretion of lytic enzymes such as chitinases and glucanases that degrade the cell walls of pathogenic fungi.

Additionally, *Trichoderma* is known to stimulate systemic resistance in host plants, enhancing their defense responses against a wide range of pathogens. These multifaceted capabilities make Trichoderma a vital component in integrated pest and disease management strategies, particularly in sustainable and organic agriculture systems.

Bacterial wilt of ginger, caused by *Ralstonia pseudosolanacearum* (Race 4, Biovar 3 strain), is one of the most destructive diseases affecting ginger (*Zingiber officinale*) cultivation, leading to significant yield losses across major growing regions. The pathogen is a soilborne, vascular-invading bacterium that induces rapid wilting and death of the host plant by colonizing the xylem vessels and disrupting water transport. Recent studies have identified *Bacillus licheniformis* as an effective biological control agent against *R. pseudosolanacearum*, offering a promising alternative to chemical management strategies. The antagonistic activity of *B. licheniformis* is attributed to multiple mechanisms that directly interfere with the pathogen's survival and virulence. These include:

- Disruption of bacterial cell structure through the formation of punctures in the cell wall, leading to cell lysis and death.
- Inhibition of biofilm formation, a critical factor in the pathogen's colonization and persistence in the plant vascular system.
- Suppression of swarming motility, which is essential for pathogen spread and successful host invasion.

The multifaceted antagonistic mechanisms exhibited by *B. licheniformis* not only reduce the population of the wilt pathogen in the rhizosphere but also impede its infection process. These attributes highlight the potential of *B.*

licheniformis as a key component in integrated disease management strategies for sustainable ginger cultivation.

Biological control of nematodes: Potential of *Pochonia chlamydosporia*

In recent years, the intensive use of chemical nematicides for the management of plant-parasitic nematodes has raised serious environmental and health concerns, leading to the progressive withdrawal and regulatory restriction of several key chemical molecules. This shift has underscored the urgent need for the development and deployment of sustainable and eco-friendly alternatives, particularly biological control agents, for effective nematode management.

Among the various biocontrol agents explored, *Pochonia chlamydosporia* has emerged as one of the most promising fungal antagonists of plant-parasitic nematodes, particularly root-knot (*Meloidogyne* spp.) and cyst nematodes (*Heterodera* and *Globodera* spp.). This filamentous ascomycete exhibits a multifaceted mode of action, including parasitism of nematode eggs, suppression of juvenile emergence, and disruption of nematode life cycles. The fungus produces a range of hydrolytic enzymes, such as proteases and chitinases, that degrade the protective layers of nematode eggs, facilitating penetration and colonization.

Importantly, *P. chlamydosporia* exhibits a high degree of rhizosphere competence, enabling it to colonize the root zone of host plants without eliciting phytotoxic effects. It can persist in the soil as a saprophyte, even in the absence of both nematode and plant hosts, thereby ensuring long-term presence and potential for biocontrol activity under field conditions. Its adaptability to diverse agro-climatic conditions and compatibility with organic farming practices make *P. chlamydosporia* a valuable component of integrated nematode management strategies aimed at reducing chemical inputs and promoting sustainable agriculture.

Harnessing Plant Growth-Promoting Rhizobacteria (PGPR) for sustainable spice production

Plant Growth-Promoting Rhizobacteria (PGPR) constitute a diverse group of root-associated bacteria that enhance plant development through a variety of direct and indirect mechanisms. These beneficial microbes colonize the rhizosphere and root surfaces, promoting seed germination, plant growth, and ultimately increasing crop productivity.

The mechanisms of PGPR-mediated plant growth promotion are broadly categorized into two types: direct and indirect.

- Direct mechanisms include the solubilization of essential nutrients such as phosphorus and potassium, biological nitrogen fixation, synthesis of phytohormones (e.g., indole-3-acetic acid, gibberellins, cytokinins), stimulation of root architecture, and mitigation of abiotic stress through the production of stress-responsive enzymes.
- Indirect mechanisms involve biological control of phytopathogens through antibiosis (production of antimicrobial compounds), secretion of lytic enzymes, competition for nutrients and ecological niches, induction of systemic resistance (ISR) in host plants.

With increasing restrictions on chemical inputs in agriculture, PGPR are gaining significant attention not only for their plant growth-promoting attributes but also for their potential as eco-friendly biocontrol agents. Their dual functionality–enhancing plant productivity while suppressing pathogens–makes PGPR a cornerstone of integrated and sustainable agricultural practices.

Microbial formulations: A sustainable solution for safe spice production

Spices, being high-value export-oriented commodities, are subject to stringent international regulations concerning pesticide residues and aflatoxin contamination. However, the widespread and indiscriminate use of chemical pesticides often leads to violations of these safety standards, posing serious threats to market access and consumer health.

To address these challenges, the adoption of biocontrol agents has emerged as a viable and environmentally sustainable alternative. The ICAR–Indian Institute of Spices Research (IISR), Kozhikode, has made significant advancements in this area by identifying and characterizing several promising microbial strains with proven efficacy against a broad spectrum of pathogens affecting spice crops.

These strains have been successfully developed into commercial biocontrol products targeting major diseases such as foot rot and slow decline in black pepper, rhizome rot & bacterial wilt in ginger etc. The deployment of such microbial technologies not only ensures compliance with residue-free production standards but also supports long-term soil and plant health, aligning with the global shift towards safer and sustainable agricultural practices.

Lime-based microbial formulations

Lime has traditionally been employed to counteract soil acidity, but simultaneous application of Lime and beneficial microorganisms like Trichoderma is not generally recommended. Farmers have to wait for a period of two to three weeks before incorporating other beneficial microorganisms in the soil. Granular lime-based formulations were developed to ameliorate soil pH and facilitate microbial delivery. To mitigate the problems due Saline/sodic soils ICAR-Indian Institute of Spices Research (ICAR-IISR), Kozhikode have successfully developed two gypsum-based bacterial formulation. The following granular formulations Tricholime, Bactolime, Bactogypsum and Trichogypsum were developed. The technology is patent filed.

- **Tricholime:** Innovative formulation combines agricultural Lime and Trichoderma in a single product. This lime-based formulation neutralizes the soil acidity while promoting plant growth and shields crops from soil-borne pathogens, all in a single application. This formulation also benefits the crop by improving the physical condition of the soil, enhancing secondary nutrient availability and by boosting soil microbial activity.
- **Bactolime:** a new granular lime-based bacterial

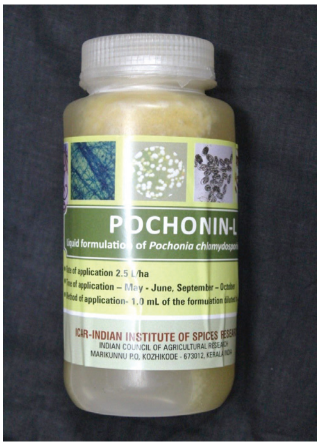
formulation that integrates beneficial bacteria (PGPRs) and lime into a single product.

- **Bactogypsum:** Designed for ameliorating high pH soils and also ensures simultaneous delivery of plant beneficial bacteria.
- **Trichogypsum:** A gypsum based *Trichoderma* formulation, for ameliorating high pH soils and ensures simultaneous delivery of *Trichoderma*.

These innovative formulations benefits the crop by improving the physical condition of the soil, enhancing secondary nutrient availability and by boosting soil microbial activity. The significance of this formulation lies in its ability to mitigate soil pH and supply bioagents concurrently, ensuring optimal plant growth and nutrient uptake. This can also boost the growth of useful microbes in soil.

Novel liquid formulation of *Pochonia chlamydosporia* for nematode management

A liquid formulation of *Pochonia chlamydosporia* (NAIMCC-SF 0048), branded as POCHONIN L, has been developed to enhance the effectiveness and shelf stability of this promising biocontrol fungus. This innovative formulation contains resting spores (chlamydospores), which contribute to its prolonged shelf life, improved viability, and enhanced field efficacy.



P. chlamydosporia is a well-documented egg-parasitic fungus effective against plant-parasitic nematodes, particularly root-knot and cyst nematodes. Its ability to colonize the rhizosphere and parasitize nematode eggs makes it an ideal component in integrated nematode management strategies.

Advantages of POCHONIN L

- Extended shelf life due to the use of durable resting spores.
- Low application rate with high efficacy.
- Targeted delivery to the root zone, where nematodes are most active.
- Compatible with organic and sustainable farming practices.

Application Protocol

- Dilute the liquid formulation at the rate of 1 mL per L of water.
- Apply as a soil drench around the root zone of target crops.

This novel formulation provides farmers and growers with a reliable, eco-friendly, and cost-effective solution for nematode management, reducing reliance on chemical nematicides while supporting soil health and crop productivity.

Biocapsules: A novel delivery system for beneficial microorganisms

A biocapsule-based delivery system (Patent No: 361021) has been developed at ICAR–Indian Institute of Spices Research (ICAR-IISR), Kozhikode, to enhance the application efficiency and shelf life of beneficial microorganisms with plant growth-promoting (PGP), mineral solubilizing, and biocontrol properties.

The encapsulation technique involves immobilizing the selected beneficial microorganism within a gelatin-based capsule matrix along with protective and stabilizing agents. The microorganisms are preserved in an inactive yet viable state, allowing them to retain high viability during storage and reactivate upon exposure to favourable environmental conditions. A single capsule can contain up to 10^{12} colony-forming units (CFU). When diluted in 100 L of water, the resulting solution maintains approximately 1 million CFU/mL, sufficient for effective field application. The formulation process is simple, cost-effective, and requires only basic laboratory facilities, operable at ambient room temperature (20–30°C).

- A range of microbial strains is available in biocapsule form (e.g., *Trichoderma* spp., *Bacillus* spp., *Azotobacter, Azospirillum, B. megaterium*).
- Correct strain selection based on crop and target outcome (growth promotion, disease suppression, nutrient mobilization) is essential.
- Application method varies based on microbial type:
- Fungal strains (e.g., *Trichoderma*): Use immediately after preparation.
- Bacterial strains: Require 8-hr incubation in sterile water before field application.

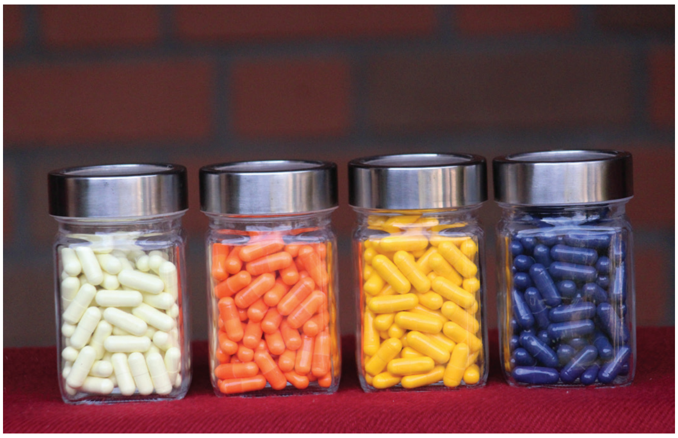
Application protocols

A. Trichoderma biocapsules:

- Dissolve 1 capsule in 1 L of water.
- After 2 hr, dilute this solution to 100–200 L with clean water.
- Apply 3–5 L per plant (e.g., mature black pepper vines) as a soil drench around the root zone.

B. Bacterial biocapsules (e.g., *Bacillus* spp, *Pseudomonas* spp):

- Dissolve 1 capsule in 1 L of sterile water (boiled and cooled).
- Incubate for 8 hr, stirring 2–3 times during the period.
- After incubation, dilute in ~200 L of clean water.
- Apply the prepared solution as a soil drench, ensuring the soil is moist and rich in organic matter for effective colonization.



Biocapsule technology offers an innovative and sustainable approach to microbial delivery in agriculture. It ensures high viability, targeted delivery, and ease of use, making it a promising tool in integrated nutrient and disease management strategies, particularly for spice crops and other horticultural systems.

Trichoprime: A biological seed coating technology for rhizomatous and tuberous crops

Seed storage losses pose a significant challenge in rhizomatous and tuberous crops such as ginger, turmeric, and yams. Conventional chemical treatments for managing storage rots often lead to ecotoxicological concerns, including development of fungicide resistance, environmental contamination, and health hazards. Hence, there is an increasing demand for eco-friendly and sustainable alternatives for disease management during storage.

Trichoprime is a biological seed coating formulation based on *Trichoderma* spp., designed to enhance seed health and viability during storage (Patent No:567347). Seed coating with *Trichoderma* prior to storage offers multiple benefits:

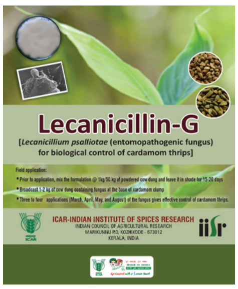
- Prevention of dry rot diseases by inhibiting the entry and colonization of storage pathogens.
- Improved seed vigour, including enhanced bud sprouting and uniform tiller emergence post-planting.
- Reduced germination time, leading to faster crop establishment.
- Protection of emerging seedlings from soil-borne pathogens in the early stages of growth.

The priming process involves treating rhizomes or tubers with Trichoprime @ 5% (w/v) before storage. The formulation acts as a biological barrier and promotes early and healthy growth during the subsequent planting season. One of the key advantages of this technology is its strain flexibility–any effective strain of *Trichoderma* spp. with proven antagonistic and growth-promoting properties can be utilized for preparing the antimicrobial coating formulation.

This technology aligns with integrated disease management (IDM) and organic farming principles, contributing to reduced chemical dependency and improved crop sustainability.

Lecanicillin-G for biological control of cardamom thrips

A technology for ecofriendly management of cardamom thrips (*Sciothrips cardamomi*) has been developed at ICAR-IISR by utilizing a naturally occurring entmopathogenic fungus *Lecanicillium psallioatae* (IISR EPF-02) isolated from cardamom thrips. Granular formulation containing *Lecanicillium psallioatae* is effective in controlling cardamom thrips and possess growth promoting traits also. The fungus attacks both juvenile and adults of cardamom thrips. The technology is patent filed.



Biological control of shoot borer, Conogethes punctiferalis, in ginger and turmeric using entomopathogenic fungus *Metarhizium pingshaense*

The entomopathogenic fungus *Metarhizium pingshaense* (IISR EPF-14) was isolated from a naturally infected larva of *Conogethes punctiferalis* (Guenée) a highly polyphagous pest. Bioassay studies revealed that the fungus is highly virulent to C. punctiferalis, causing over 86% mortality in fifth instar larvae at a concentration of 1 × 10^8 spores/mL. The median lethal concentration (LC_{50}) was determined to be 9.1 × 10^5 conidia/mL, while the median survival time (MST) for late instar larvae was 4.7 and 6.4 days at concentrations of 1 × 10^8 and 1 × 10^7 conidia/mL, respectively. The recommended technology involves spraying *M. pingshaense* at a concentration of 1 × 10^7 conidia/mL, beginning in the second fortnight of July (approximately 45 days after planting) and continuing until the first fortnight of November, at 21-day intervals.

Sporulating cadaver of Conogethes puntiferalis infected by Metarhizium pingshaense

Arbuscular mycorrhizal (AM) fungi for spices

Arbuscular mycorrhizal (AM) fungi are vital biostimulants that form symbiotic relationships with most plants, including key spice crops like black pepper, ginger, turmeric, and cardamom. These fungi act as biofertilizers, bioprotectors, and bioregulators by extending the plant's root system through their hyphae, significantly improving the uptake of immobile nutrients such as phosphorus, zinc, and copper. This mutual association also enhances drought tolerance, disease resistance, and soil structure. Observations show that AM fungal spores are common in spice crop soils, with a strong positive correlation between root colonization and plant performance, particularly in black pepper. Inoculation with AM fungi not only boosts growth and nutrient absorption but also activates genes related to systemic resistance, strengthening the plant's defense mechanisms.

Effect of AM fungi on spice crops

- The fortification of spice crops like ginger, turmeric, cardamom, and black pepper with AM fungi offers a host of benefits.
- AM fungi play a crucial role in enhancing phosphorus absorption, leading to improved growth and higher yields.
- Their ability to suppress root pathogens and enhance water-use efficiency contributes to healthier plants, reducing the reliance on chemical inputs and promoting sustainability in spice production.

- Studies have shown that the presence of AM fungi in spice plants can increase root and shoot biomass, enhance nutrient uptake, and decrease disease occurrence.
- In ginger cultivation, AM fungi demonstrate effectiveness in mitigating soil-borne diseases such as soft rot caused by pathogens like *Pythium* species.
- By strengthening the root system, these fungi enhance plant vigor and resistance to such diseases.
- The association of AM fungi with black pepper boosts defense-related enzymes, particularly peroxidases, offering protection against diseases.
- Inoculation with AM fungi increases soil enzyme activity and promotes beneficial microbes in the rhizosphere of black pepper and turmeric.
- Cardamom seedlings grown in AM fungi enriched media exhibit early vigor and resistance to infections caused by Fusarium species.

Talc based formulation of *Trichoderma asperellum*

A talc-based formulation of *Trichoderma asperellum* (NAIMCC-SF 0049) can be effectively multiplied and applied using a simple on-farm enrichment technique. For mass multiplication, 1–2 kg of the formulation is mixed with 100 kg of a dry substrate comprising powdered cow dung and neem cake in a 90:10 ratio. The mixture should be moistened by sprinkling water to achieve a damp consistency, thoroughly homogenized, and then covered with a perforated polyethylene sheet or newspaper. It is incubated in a shaded area for 10–14 days. After one week, the mixture should be turned to facilitate uniform multiplication and maintained for the remaining period.

While cow dung alone can serve as a suitable growth medium, the combination of cow dung and neem cake enhances the quality and efficacy of the formulation. The enriched *Trichoderma*-inoculated substrate can be incorporated into potting mixtures, nursery beds, or field soils.

For black pepper cultivation, the following application schedule is recommended

- At the onset of the monsoon (May–June), apply 1–2 kg of the enriched mixture per vine around the base of the plant.
- A second application may be given during August–September.
- Alternatively, the talc-based formulation can be directly applied at 50 g per vine, twice annually–during April–May and again in September–October.

For nursery applications, the talc formulation may be added at 1 g per kg of soil during the preparation of nursery mixtures in polybags.

Talc based formulation of *Pochonia chlamydosporia*

A talc-based formulation of *Pochonia chlamydosporia* (NAIMCC-SF 0048), a potent biological control agent against plant-parasitic nematodes, can be effectively utilized for soil and root zone application in black pepper. For field-scale use, 1–2 kg of the formulation may be mixed with 20 kg of moistened, dry powdered cow dung, which serves as an ideal organic carrier and substrate for fungal establishment.

The prepared mixture can be incorporated into potting mixtures, nursery beds, and field soils to facilitate early colonization and enhance the suppressive effect against nematodes. In black pepper plantations, application is recommended as follows:

- At the onset of the monsoon (May–June), apply 1–2 kg of the enriched mixture per vine, distributed around the plant base.
- A second application may be given during August–September to ensure continued root protection and nematode suppression.

Alternatively, the talc-based formulation of P. *chlamydosporia* may be applied directly at 50 g per vine, twice annually–once during April–May and again during September–October.

Integrated management strategy for bacterial wilt of ginger

An integrated disease management (IDM) technology was developed for the effective control of bacterial wilt in ginger, caused by *Ralstonia pseudosolanacearu*m. This strategy integrates physical, chemical, and biological approaches to provide a sustainable and holistic solution to disease management.

The IDM package comprises

- Physical method: Soil solarization for 45–55 days using transparent polyethylene sheets, which effectively reduces the soilborne inoculum load by elevating soil temperatures.
- Chemical method: Soil amelioration with calcium chloride, which enhances soil health and contributes to pathogen suppression.
- Biological method: Application of the ginger-associated apoplastic bacterium, *Bacillus licheniformis* (MTCC 12725), which exhibits strong antagonistic activity against the wilt pathogen.

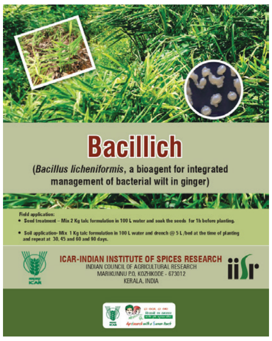
The integration of soil solarization followed by rhizome priming with *B. licheniformis* was found to significantly reduce disease incidence and enhance plant vigour. To facilitate field-level adoption, a talc-based formulation of *B. licheniformis* was commercialized under the name ‘Bacillich’, and the technology was further advanced through encapsulation to improve microbial viability and delivery efficiency.

The recommended application protocol includes; Rhizome treatment: Soaking seed rhizomes in a 2% Bacillich suspension (2 kg in 100 L of water) prior to planting.

Soil drenching: Application of 1% Bacillich suspension at the time of planting and repeated at 30, 45, 60, and 90 days after planting, depending on disease pressure.

This integrated strategy offers an effective, environmentally safe, and farmer-friendly approach for managing bacterial wilt in ginger.

PGPR-based consortium for enhanced growth and yield in black pepper



IISR Biomix is a talc-based microbial consortium formulated for promoting plant growth and improving yield in black pepper. The formulation comprises a synergistic mix of Plant Growth-Promoting Rhizobacteria (PGPR), including *Bacillus amyloliquefaciens, B. megaterium* and *Acinetobacter* sp. These strains enhance plant health through mechanisms such as nutrient solubilization, phytohormone production, and suppression of soilborne pathogens.

Application guidelines

Water-Based Application Technique:

- Mix 20 g of IISR Biomix in 1 L of water.
- Apply 250 mL of the suspension per black pepper vine in the field.
- In nursery conditions, apply 100 mL per polybag.

Farmyard Manure Enrichment Method:

- Mix 1 kg of IISR Biomix with 100 kg of well-decomposed farmyard manure (FYM) or cow dung.
- Apply the enriched mixture at 1 kg per vine, placed around the root zone (basin application).

Application Schedule: Apply twice annually, ideally during the pre-monsoon (May–June) and post-monsoon (September–October) periods for maximum efficacy.

The dual mode of application and the robust microbial consortium make IISR Biomix an effective bio-input for sustainable black pepper cultivation, contributing to improved nutrient uptake, stress tolerance, and overall crop productivity.

PGPR talc formulations for enhanced growth and yield in spices

Talc-based formulations of Plant Growth-Promoting Rhizobacteria (PGPR) have shown significant potential in enhancing nutrient use efficiency, plant growth, and crop productivity in spices.

IISR Biopower G (*Bacillus amyloliquefaciens*): This formulation is specifically recommended for ginger. It promotes root and shoot growth, enhances nutrient mobilization, and improves overall yield. Seed rhizome treatment: 10 g/L of water, Soil application (drenching): 2 kg/ha at 30 and 60 days after planting

IISR Biopower SS (*Pseudomonas putida* and *Mycobacterium paraoxidans*): This talc formulation is designed for use in seed spice crops. These PGPR strains contribute to better nutrient availability and promote robust plant growth.

Soil application: 1 kg/ha at 30 days after planting

Both formulations support sustainable crop production by reducing dependency on chemical fertilizers and promoting plant health through microbial activity in the rhizosphere.

Seed coating formulations of PGPR

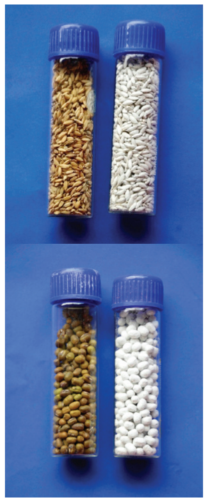
Seed coating technologies using beneficial microorganisms offer an effective method to enhance seed health, germination, and crop performance, particularly under organic and low-input agricultural systems.

A PGPR-based seed coating formulation developed utilizing *Pseudomonas putida* and *Mycobacterium paraoxidans*, both known for their plant growth-promoting attributes. These bacteria facilitate early seedling vigor, nutrient mobilization, and resistance to soilborne pathogens.

Application Protocol

- The formulation is applied at a rate of 10 g/L of water for seed coating.
- Coating is carried out under controlled temperature conditions to ensure optimal adhesion and viability of microbial cells.
- Once coated, seeds can be stored at ambient room temperature without loss of efficacy.

Advantages



- Suitable for all types of seeds, including seed spices and horticultural crops.
- Coated seeds exhibit resistance to storage pests, ensuring seed quality during storage.
- Enhanced germination rates and seedling establishment under field conditions.
- Yield improvement ranging from 15–30% has been observed in various trials.
- The technology is compatible with organic farming systems, offering a sustainable alternative to chemical seed treatments.

Best practices for the effective use of biocontrol agents

- Maintain Adequate Soil Moisture: Ensure that the soil has sufficient moisture at the time of application to facilitate the survival, colonization, and activity of the biocontrol agents.
- Enrich Soil with Organic Matter: Incorporate well-decomposed organic manures or compost into the soil to provide a favourable environment and nutrient base that supports the growth and sustenance of beneficial microbial populations.
- Avoid Co-application with Chemical Pesticides: Do not mix biocontrol formulations with chemical pesticides or fungicides, as these can inhibit or kill the beneficial microorganisms.
- Maintain a Safe Interval with Chemical Treatments: Allow a minimum interval of 7–10 days between the application of chemical pesticides and biocontrol agents to minimize antagonistic interactions and ensure microbial efficacy.
- Proper Storage Conditions: Store biocontrol formulations in a cool, dry place, away from direct sunlight and excessive heat to preserve microbial viability and shelf life.

- Timely Use of Substrate-Based Cultures: Avoid storing biocontrol agents that are mass-multiplied on organic substrates for extended durations, as prolonged storage can lead to a decline in viability and effectiveness.

As export-oriented commodities, spice crops must comply with stringent food safety standards set by importing countries, particularly concerning pesticide residues and contaminants. Growing international concern over the environmental and health hazards associated with the excessive use of synthetic pesticides has further emphasized the need for safer, sustainable alternatives. In this context, beneficial microorganisms with proven biocontrol potential and plant growth-promoting (PGP) traits offer a promising substitute for chemical inputs. These microbes can suppress phytopathogens through mechanisms such as antibiosis, competition, and induced systemic resistance, while also enhancing crop productivity by improving nutrient uptake, soil health, and stress tolerance. Utilization of such bioinoculants is a key component of sustainable agricultural practices, enabling spice producers to meet global quality standards while minimizing ecological impact.

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