AGRI MAGAZINE
(International E-Magazine for Agricultural Articles)
Volume: 03, Issue: 10 (October, 2026)
Available online at http://www.agrimagazine.in
©Agri Magazine, ISSN: 3048-8656

Seed Treatment with Biocontrol Agents: Giving Seeds a Healthy Start for Sustainable Crop Production

*Niranjan Prasad[1], Sandeep Adavi[1], Ajay Kumar Verama[1], P Mooventhan[1], Yogesh Yele[1] and Harish M N[2]
[1]ICAR-National Institute of Biotic Stress Management, Baronda, Raipur, Chhattisgarh, 493225, India
[2]ICAR-Agricultural Technology Application Research Institute, Jabalpur, Madhya Pradesh 482004, India
*Corresponding Author's email: niranjaniariseed@gmail.com

Seed is the foundation of crop production, and successful crop establishment depends greatly on its physiological and biological health. Seed- and soil-borne pathogens can compromise germination, seedling vigour and early plant establishment, while repeated dependence on chemical seed treatments raises concerns regarding environmental sustainability, pesticide resistance and disruption of beneficial soil microorganisms. Biological seed treatment offers an environmentally compatible alternative by introducing beneficial microorganisms directly onto the seed before sowing. Biocontrol agents such as *Trichoderma*, *Bacillus* and *Pseudomonas* can establish around the germinating seed and developing root system, where they suppress pathogens through competition, antibiosis, mycoparasitism, production of hydrolytic enzymes and induction of plant defence responses. Beyond disease suppression, these microorganisms can contribute to nutrient mobilization, root development and improved seedling vigour, thereby supporting stronger crop establishment. The concept is increasingly shifting from simply protecting seeds against pathogens towards establishing a beneficial microbial environment around the emerging plant. This article highlights the principles, major microbial agents, mechanisms of action, practical approaches and opportunities associated with biological seed treatment. Particular emphasis is given to the role of seed-associated microbial interactions, formulation quality, microbial compatibility and integration with other crop-management practices. Advances in microbial consortia, seed microbiome engineering and precision delivery technologies are expected to further enhance the reliability and field-level effectiveness of biological seed treatment. Integrating beneficial microorganisms with quality seed and other sustainable crop-protection practices can contribute to healthier crops, reduced dependence on chemical inputs and more resilient agricultural production systems.

Keywords: Biological seed treatment, biocontrol agents, seed health, seedling vigour. sustainable agriculture.

Introduction

A healthy crop begins with a healthy seed. Although seeds appear dry, dormant and inactive, they are living biological systems containing the embryo, stored reserves and a diverse community of microorganisms associated with their surface and internal tissues. Immediately after sowing, the seed enters a highly dynamic phase in which water uptake, metabolic activation, enzymatic processes and radicle emergence occur rapidly. At this stage, the germinating seed and young seedling are particularly vulnerable to seed-borne and soil-borne pathogens. Poor seed health may result in delayed and uneven germination, reduced seedling vigour, abnormal seedlings, pre- and post-emergence mortality and poor crop establishment,

ultimately reducing yield potential (Lamichhane et al., 2018). Therefore, protecting the seed during the initial stages of germination is fundamental to establishing a vigorous and productive crop.

Seed treatment represents one of the simplest, most targeted and economical approaches to protect seeds and seedlings during this vulnerable period. Conventional seed treatment has largely relied on chemical fungicides and insecticides because of their rapid and predictable protective action. However, repeated and indiscriminate use of chemical pesticides has raised concerns regarding pesticide residues, environmental contamination, disruption of beneficial soil microorganisms and the emergence of pesticide-resistant pathogen populations. These challenges have created a growing need for safer and biologically based alternatives that can provide effective seed protection while supporting soil biological health. Biological seed treatment offers such an approach by shifting the emphasis from chemical eradication of pathogens towards the establishment of beneficial microorganisms around the germinating seed (Adeboye et al.,2025).

Biocontrol agents (BCAs) are beneficial microorganisms capable of suppressing plant pathogens through multiple mechanisms. Fungal and bacterial agents such as *Trichoderma*, *Bacillus* and *Pseudomonas* can be applied to seed through coating, dressing or other suitable inoculation methods. Following sowing, these microorganisms establish themselves on the seed surface and in the spermosphere and rhizosphere, where they compete with pathogens for nutrients and colonization sites. Some produce antimicrobial metabolites, siderophores and pathogen-degrading enzymes, while others directly antagonize pathogenic fungi or stimulate the plant's innate defence mechanisms. Thus, the value of biological seed treatment extends beyond direct pathogen suppression; beneficial microorganisms can also influence root architecture, nutrient acquisition and early seedling development, creating a more favourable biological environment for crop establishment (Cardarelli et al., 2022).

The concept of biological seed treatment is therefore evolving from “protecting the seed from pathogens” to “engineering a beneficial microbial environment around the seed.” By delivering selected microorganisms directly to the seed, the treatment provides beneficial microbes with an early opportunity to establish before or alongside invading pathogens. This targeted delivery can reduce the quantity of biological input required and potentially improve the consistency of microbial establishment compared with broad soil application. With increasing interest in sustainable agriculture, integrated pest and disease management, reduced pesticide dependence and soil health restoration, biocontrol-based seed treatment has considerable potential as a practical technology for modern crop production. The future of this approach lies in developing robust microbial formulations, compatible microbial consortia and seed-specific delivery technologies that can perform reliably under diverse field conditions.

What is biological seed treatment?

Biological seed treatment is the practice of applying beneficial microorganisms or their formulations directly to seeds before sowing. Depending on the crop, formulation and delivery technology, the treatment may involve seed coating, seed dressing, slurry treatment or microbial inoculation. The purpose is not simply to eliminate pathogens from the seed surface; rather, it is to establish a population of beneficial microorganisms around the seed at the very beginning of crop development. When the treated seed absorbs water and begins to germinate, these microorganisms become active and establish themselves around the emerging radicle and young root, creating a biologically active zone at the point where the plant first interacts with the soil environment (Welbaum et al., 1998).

The real strength of biological seed treatment lies in the multiple ways through which beneficial microorganisms interact with pathogens and the plant itself. Biocontrol agents may compete with pathogens for nutrients and infection sites, produce antimicrobial metabolites and siderophores, release enzymes that degrade pathogen structures, or directly antagonize and parasitize harmful fungi. At the same time, some beneficial microbes can improve nutrient availability, stimulate root development and activate the plant's own defence

machinery, thereby preparing the young plant to respond more effectively to subsequent pathogen attack (Hossain et al., 2017). In this sense, biological seed treatment can be viewed as a precision delivery of beneficial microbes to the right place at the right time—placing the plant's microbial allies around the seed before disease pressure becomes established.

Biological seed treatment involves coating, dressing or inoculating seeds with beneficial microorganisms or their formulations before sowing (Rocha et al., 2019). The objective is not merely to kill pathogens but to establish a beneficial microbial population around the germinating seed. Beneficial microorganisms introduced through seed treatment can multiply around the emerging seedling and compete with harmful microorganisms for nutrients and space. Unlike a conventional chemical treatment that primarily acts through toxicity, biocontrol agents may operate through several biological mechanisms simultaneously. These include competition for nutrients and colonization sites, production of antimicrobial compounds, secretion of pathogen-degrading enzymes, parasitism or direct antagonism, nutrient mobilization and stimulation of the plant's own defence mechanisms.

Important biocontrol agents for seed treatment

1. *Trichoderma*: The fungal guardian

Species of *Trichoderma* are among the most extensively studied fungal biocontrol agents used in agriculture. *T. viride*, *T. harzianum* and *T. virens* are commonly associated with biological management of soil- and seed-borne diseases. *Trichoderma* can colonize the seed and developing root zone, where it competes with pathogens for nutrients and space. It may also produce antimicrobial metabolites and hydrolytic enzymes capable of attacking fungal pathogens. In addition, some strains stimulate plant defence responses and promote root development (Hashem et al., 2019). Seed treatment with *Trichoderma* has been used against several soil-borne pathogens, including *Rhizoctonia*, *Fusarium*, *Pythium*, *Phytophthora* and *Sclerotium*. Indian recommendations have included *T. viride* and related species for seed treatment against soil-borne diseases.

Table 1. Major biocontrol agents used for biological seed treatment

Biocontrol agent	Major mechanism	Target pathogens/diseases	Major additional benefit
Trichoderma harzianum	Mycoparasitism, antibiosis, competition, induced resistance	*Fusarium*, *Rhizoctonia*, *Pythium*, *Sclerotium*	Root growth and plant defence
Trichoderma viride	Mycoparasitism, enzyme production, competition	Seed- and soil-borne fungal pathogens	Improved seedling establishment
Bacillus subtilis	Antibiosis, competition, induced systemic resistance	*Fusarium*, *Rhizoctonia*, *Pythium* and bacterial pathogens	Plant-growth promotion
Bacillus amyloliquefaciens	Lipopeptide production, competition, induced resistance	Soil- and seed-borne pathogens	Root development and nutrient acquisition
Pseudomonas fluorescens	Siderophore production, antibiosis, competition, induced resistance	*Fusarium*, *Rhizoctonia*, *Pythium* and other soil-borne pathogens	Rhizosphere colonization and growth promotion
Bacillus spp. + *Trichoderma* spp.	Complementary antagonistic mechanisms	Complex pathogen pressure	Potential synergistic bioprotection

2. *Bacillus*: Beneficial bacteria with staying power

Species of *Bacillus* are particularly attractive as biological seed-treatment agents because many species produce resistant endospores. These spores provide greater stability during formulation, storage and application than many non-spore-forming bacteria. *Bacillus subtilis*, *B. amyloliquefaciens* and related beneficial bacteria can colonize the seed and rhizosphere and suppress pathogens through antimicrobial compounds, competition and induction of plant defence. Their ability to survive under relatively harsh conditions makes *Bacillus*-based formulations promising candidates for commercial biological seed treatment (Vasques, et al., 2024).

3. *Pseudomonas*: Microbial partners around the root

Beneficial *Pseudomonas* species are another important group of bacteria used in biological crop protection. *Pseudomonas fluorescens*, for example, has been used as a seed treatment and foliar biocontrol agent. These bacteria can rapidly colonize the developing root zone and suppress pathogens through competition, production of antimicrobial substances and siderophores, and stimulation of plant defence responses. Some strains can also contribute to plant growth promotion (Sivasakthi et al., 2014).

4. Plant-growth-promoting microorganisms

Biological seed treatments need not be restricted to disease suppression. Several beneficial microorganisms can simultaneously enhance plant growth and nutrient acquisition. Microbial inoculants may improve nutrient availability, stimulate root growth and enhance seedling vigour. Consequently, the benefits of biological seed treatment can extend beyond disease management to better crop establishment and improved plant performance (Rocha et al., 2019).

How do biocontrol agents protect the seed?

The success of biological seed treatment depends on several complementary mechanisms.

Competition: Beneficial microorganisms colonize the seed and rhizosphere, occupying ecological niches and consuming nutrients that would otherwise be available to pathogens.

Antibiosis: Certain BCAs produce antimicrobial compounds that inhibit or suppress harmful microorganisms.

Mycoparasitism: Some *Trichoderma* species directly interact with pathogenic fungi, colonize their hyphae and degrade their cell walls using enzymes.

Induced resistance: Beneficial microbes can stimulate the plant's natural defence machinery, preparing the young plant to respond more rapidly to pathogen attack.

Nutrient acquisition: Some beneficial bacteria mobilize nutrients or produce compounds that improve nutrient availability and root development.

Root colonization: Effective BCAs establish themselves around the developing root system, providing protection during the vulnerable early stages of crop growth.

These multiple mechanisms are one reason why biological control can fit well into an integrated disease-management programme rather than functioning simply as a replacement for a chemical pesticide.

How to treat seed with biocontrol agents?

Biological seed treatment is relatively simple and can be carried out at the farm level when a properly formulated and officially recommended product is available.

Step 1: Select healthy seed: Use clean, high-quality seed with good germination and physical purity. Biological treatment cannot compensate for severely deteriorated or poor-quality seed.

Step 2: Select a suitable biocontrol formulation: Choose a quality formulation containing a properly identified and viable biocontrol strain. The product should be used according to the label and recommendations of the agricultural university, KVK or relevant agricultural authority.

Step 3: Prepare the treatment mixture: For dry formulations, the recommended quantity is mixed uniformly with the required quantity of seed. A suitable sticker or adhesive may be

used when recommended to improve attachment of microbial cells or spores to the seed surface.

Step 4: Coat the seed uniformly: The seed should be thoroughly mixed until the microbial formulation covers the seed surface evenly. Uneven coating can result in inconsistent establishment of the biocontrol agent.

Step 5: Shade-dry and sow: After treatment, seeds should generally be dried in shade and sown as soon as practical, following the product-specific instructions. Excessive exposure to direct sunlight, heat or incompatible chemicals can reduce microbial viability.

Importantly, the recommended dose should always be followed for the particular crop and formulation. For example, seed-treatment with approximately 4–10 g/kg seed for certain *Trichoderma* formulations and 10 g/kg seed for some *Pseudomonas fluorescens* and *Bacillus subtilis* formulations. These values should not be generalized to every commercial product because formulation strength and label recommendations vary.

Can biological and chemical seed treatments be combined?

This is an important practical question. Biocontrol agents are living organisms. Therefore, indiscriminate mixing with fungicides, bactericides or other chemicals can reduce their survival and effectiveness. Compatibility varies considerably among microbial strains and chemical active ingredients. Farmers should therefore avoid tank-mixing or simultaneously applying microbial inoculants with chemical seed treatments unless compatibility has been scientifically established or specifically recommended on the product label. Where an integrated programme is required, the sequence, interval and compatibility should follow validated recommendations. The objective should be to protect both the seed and the beneficial microbial population.

What makes a biological seed treatment successful?

The effectiveness of a BCA depends on much more than simply putting microbes on seeds. Several factors influence the final outcome:

- Viability and quality of the microbial formulation
- Correct dose and uniform seed coating
- Compatibility with other seed-treatment products
- Seed quality and physiological status
- Soil temperature and moisture
- Soil type and microbial community
- Pathogen pressure
- Ability of the BCA to colonize the seed and rhizosphere
- Crop genotype and growth stage

This explains why a biocontrol treatment that performs exceptionally well in one location may show a different level of effectiveness under another set of environmental conditions. Recent research increasingly emphasizes that biological seed treatment is influenced by the interaction between microbial strain, crop genotype, seed physiological status and environmental conditions.

Biological seed treatment: more than disease control

One of the most exciting aspects of biological seed treatment is that its benefits may extend beyond pathogen suppression. A global meta-analysis covering 396 studies reported that biological seed treatments, compared with untreated seeds, were associated on average with improvements in germination, seedling emergence, plant biomass, disease control and crop yield. The reported average effects were approximately 7% higher germination, 91% higher seedling emergence, 53% higher plant biomass, 55% better disease control and 21% higher crop yield, although the magnitude of response varied substantially among crops and experimental conditions. These findings highlight an important principle: a biological seed treatment can function as both a protective shield and a biological starter for the crop (Lamichhane et al., 2022).

Role in integrated pest and disease management

Biological seed treatment should not be viewed as an isolated technology. It works best as one component of Integrated Pest Management (IPM) and integrated disease management.

A practical approach may include:

Quality seed → biological seed treatment → balanced nutrition → proper irrigation → field sanitation → resistant/tolerant varieties → monitoring → need-based intervention

This approach reduces dependence on routine chemical applications and encourages the conservation of beneficial microorganisms. Biological seed treatment is particularly attractive because only a relatively small quantity of microbial formulation is required to treat a large quantity of seed, and the beneficial organism is delivered directly to the location where early protection is required.

From single microbes to microbial communities

The next generation of biological seed treatment may move beyond the use of a single microorganism. Plants naturally interact with complex communities of bacteria and fungi. Researchers are therefore exploring microbial consortia, synthetic microbial communities and seed-associated microbiomes in which several compatible microorganisms work together. Such approaches could combine different functions—for example, one microorganism may suppress pathogens, another may improve nutrient availability, while another may stimulate plant defence or root growth. However, microbial consortia require careful selection because microorganisms do not always cooperate with one another. Compatibility, stability, colonization ability and consistency under field conditions must be established before widespread adoption.

Practical precautions for farmers

For successful biological seed treatment, farmers should remember the following:

1. Always use a quality-assured microbial formulation from a reliable source.
2. Check the crop-specific label recommendation and microbial viability before treatment.
3. Do not use expired or poorly stored formulations.
4. Treat only good-quality seed.
5. Ensure uniform coating of the seed.
6. Protect treated seed from excessive heat and direct sunlight.
7. Do not mix BCAs indiscriminately with fungicides or other chemicals.
8. Follow recommended doses rather than assuming that a higher dose will always give better control.
9. Maintain proper soil moisture after sowing to support microbial establishment.
10. Use biological seed treatment as part of an integrated crop-management strategy, not as a stand-alone solution.

Looking ahead

Agriculture is entering an era in which crop protection must deliver productivity without compromising soil health, biodiversity and environmental sustainability. In this transition, the seed provides an ideal point of intervention. Instead of waiting for a disease to appear in the field, beneficial microorganisms can be introduced at the beginning of the crop cycle. They can accompany the seed during germination, establish around the emerging root and interact with the plant when it is most vulnerable. The future of biological seed treatment will increasingly depend on better microbial strains, improved formulations, longer shelf life, precise delivery systems, microbial consortia and a deeper understanding of seed–microbe–soil interactions. The concept is simple but powerful: protect the seed, support the seedling and strengthen the crop from the very beginning.

Conclusion

Seed treatment with biocontrol agents represents a practical bridge between modern microbiology and sustainable agriculture. Beneficial fungi and bacteria such as *Trichoderma*, *Bacillus* and *Pseudomonas* can help suppress seed- and soil-borne pathogens while

supporting plant establishment and growth. For farmers, the message is straightforward: a few minutes spent treating seed correctly before sowing can influence the health of the crop for weeks afterward. For researchers, the challenge is to develop microbial formulations that are reliable, affordable, compatible and effective under diverse field conditions. As agriculture moves towards reduced chemical dependence and greater biological intensification, the future of crop protection may begin not with the spray tank, but with a biologically protected seed placed in the soil.

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