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Biological Control Agents: A Sustainable Solution for Vegetable Disease Management

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Abstract

Vegetables provide fibre, vitamins, minerals and antioxidants that lower the risk of heart disease, cancer and other non-communicable illnesses, yet global intake remains below the recommended five daily servings, contributing to millions of deaths each year. Meanwhile, fungal, bacterial and oomycete pathogens can eliminate up to a third of vegetable yield before or after harvest. Broad-spectrum pesticides help protect crops, but residues, non-target impacts and rising pathogen resistance have narrowed their long-term usefulness. These constraints have shifted interest toward biological control agents (BCAs)—beneficial bacteria, fungi and yeasts that suppress pathogens by competition, direct antagonism and priming of plant defences. BCAs integrate easily into Integrated Pest Management programmes, reduce chemical inputs and safeguard both soil health and consumer safety. This review outlines the main BCA groups, explains their modes of action and discusses why they are becoming an essential pillar of sustainable vegetable disease management.

Introduction

Vegetables are central to balanced diets, supplying micronutrients, dietary fibre and bioactive compounds that guard against cardiovascular disease, obesity and several cancers. Low fruit-and-vegetable intake is now flagged by the WHO as a top lifestyle risk factor. Crop supply, however, is constantly undermined by pathogens. Soil-borne fungi such as *Fusarium oxysporum* and *Rhizoctonia solani*, water-moulds like *Pythium spp.*, and foliar pathogens including *Botrytis cinerea* can wipe out seedlings, rot roots or spoil fruit, together eroding roughly 30% of attainable vegetable yield—losses valued in the hundreds of billions of dollars. For decades growers have leaned on synthetic fungicides and bactericides, but intensive use has bred resistant strains, inflated production costs and left residues that alarm regulators and consumers. Collateral damage to beneficial soil biota and pollinators further weakens agro-ecosystem resilience. Biological control offers a viable alternative. BCAs—chiefly strains of *Bacillus*, *Pseudomonas*, *Trichoderma* and antagonistic yeasts—crowd out pathogens, secrete antifungal metabolites, parasitise mycelia or trigger plant immune responses. Naturally occurring and largely host-specific, they leave no toxic residues and combine well with cultural tactics and low-risk chemicals in IPM. Commercial products are already on the market, and research into multi-strain consortia and shelf-stable carriers is accelerating their practical adoption.

Role of Bio-control Agents in Vegetable Disease Management

The increasing demand for chemical-free, residue-safe vegetables has heightened the need for sustainable disease management methods, and biological control agents (BCAs) have become central to this shift. BCAs are beneficial microbes—mostly bacteria, fungi, and yeasts—that protect vegetables through natural ecological mechanisms. Their application is particularly valuable in managing diseases in commonly cultivated vegetables such as tomato, brinjal, okra, chilli, cucurbits, cabbage and cauliflower.

Vegetable crops, due to their dense planting and frequent irrigation, create conditions that favour pathogens. Tomato, for example, suffers from Fusarium wilt, Bacterial spot and Early blight; okra faces root rots and viral infections; cabbage and cauliflower deal with black rot and clubroot. Using BCAs such as *Trichoderma harzianum* to suppress *Fusarium* in tomato and okra, *Bacillus subtilis* for controlling *Alternaria* in cabbage, or *Pseudomonas fluorescens* to manage damping-off in cucurbits shows their wide applicability.

These agents act by competing for resources and infection sites, releasing inhibitory substances (antibiosis), degrading pathogen structures (mycoparasitism), and priming the plant's systemic defences. This multi-pronged action makes BCAs a strong and sustainable tool, especially in Integrated Pest Management (IPM), reducing the need for synthetic inputs and enhancing soil and plant health over time.

Mechanisms of Action of Bio-control Agents in Vegetable Crops

The mechanisms by which biocontrol agents act are both diverse and highly effective, giving them significant potential in managing vegetable diseases. One of the most important methods is competitive exclusion, where BCAs rapidly colonize the root surface or leaf tissues, leaving no space or nutrients for the pathogens. For instance, *Pseudomonas fluorescens* applied as a seed coat on tomato or okra forms a biofilm on roots, preventing the attachment and establishment of pathogens like *Ralstonia solanacearum*.

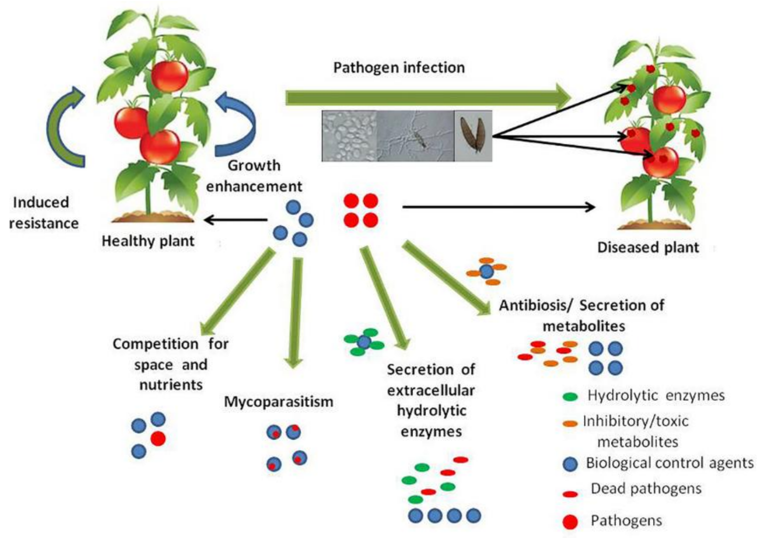

Fig 1. Mode of Action of Biocontrol Agents

Another major mechanism is antibiosis, where the biocontrol agent produces secondary metabolites like antibiotics or toxins that directly inhibit the growth of pathogens. *Bacillus subtilis*, used in cabbage and chili, secretes compounds such as iturin and surfactin that damage fungal membranes and prevent infection.

Mycoparasitism is a mode of action particularly effective against soil-borne fungal pathogens. For example, *Trichoderma harzianum* attacks the hyphae of *Fusarium oxysporum* in crops like cucumber and tomato. It coils around the fungal threads, penetrates them using enzymes like chitinase and cellulase, and ultimately breaks down the pathogen.

Enzymatic degradation is another strategy used by several BCAs. *Bacillus amyloliquefaciens* and other rhizobacteria produce a cocktail of enzymes that dissolve the structural components of pathogens. In pepper plants, these enzymes can break down sclerotia of *Sclerotinia sclerotiorum*, effectively controlling stem rot.

Iron competition through siderophore production is another indirect but effective mechanism. *Pseudomonas spp.* produce iron-binding molecules that deprive pathogens of this essential micronutrient. In cucumber nurseries, this activity limits *Pythium* growth and enhances seedling survival. Induced systemic resistance (ISR) is a crucial biological defence where the BCA doesn't act on the pathogen directly but triggers the plant's own defence systems. For example, seed treatment of okra with *Bacillus velezensis* activates internal signalling pathways, which prepare the plant for faster and stronger responses to later pathogen attacks.

Biofilm formation by BCAs like *Azotobacter chroococcum* adds a physical barrier to infection, especially in crops like bottle gourd and beans, while also maintaining moisture levels and improving nutrient uptake.

Lastly, many BCAs also enhance plant growth by producing phytohormones like auxins or gibberellins and solubilizing soil nutrients. When applied to vegetables such as bell pepper or tomato, such BCAs not only suppress disease but also improve overall crop vigour and resilience, making them a dual-purpose tool in sustainable agriculture.

Field-Level Implementation and Operational Challenges

Biocontrol agents show their greatest potential when strategically implemented in diverse cropping systems. In vegetable cultivation, BCAs can be introduced via seed treatment, soil enrichment, foliar application, or integration with drip irrigation. For example, coating seeds of okra and cowpea with *Trichoderma asperellum* offers early protection from seed- and soil-borne pathogens. Similarly, *Pseudomonas fluorescens* applied in the nursery stage or via soil drenching before cucumber transplanting helps prevent damping-off and stimulates early growth. Foliar applications of *Bacillus subtilis* in crops like tomato and brinjal offer effective protection against aerial pathogens such as early blight and anthracnose. These practices work synergistically with botanicals, trap crops, crop rotation, and resistant varieties, strengthening the overall framework of Integrated Pest Management (IPM).

However, successful field implementation comes with practical challenges. The efficacy of BCAs can vary significantly with environmental factors like temperature, humidity, and soil pH. For instance, dry or nutrient-poor soils may reduce colonization and persistence of *Trichoderma*. Unlike chemical fungicides, BCAs often act preventively and may require multiple applications to maintain their activity. Compatibility with other agrochemicals, especially fungicides, can limit their usage, as some synthetic products can harm or inhibit the biocontrol microbes. Additionally, the living nature of BCAs demands proper formulation, storage, and transport infrastructure to maintain their viability. Ensuring quality control, shelf stability, and ease of application are ongoing hurdles for commercial adoption. Despite these issues, research into formulation technologies, encapsulation methods, and co-application strategies is steadily addressing these limitations and improving their reliability under farm conditions.

Conclusion

Biological control agents are rapidly emerging as essential components of sustainable vegetable production systems. By offering targeted, residue-free protection against a wide array of pathogens, BCAs serve as reliable alternatives to synthetic pesticides while supporting long-term agro-ecosystem health. Their use in crops like tomato, okra, chili, cabbage, and cucurbits has already shown promising outcomes in managing soil-borne and foliar diseases through multiple ecological mechanisms.

Looking ahead, innovations are further expanding their utility. Multi-strain consortia, advanced encapsulation methods (such as alginate beads and biochar carriers), and the exploration of endophytic BCAs—microbes that colonize internal plant tissues—are enhancing field-level stability and persistence. Moreover, genetic tools such as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) are being investigated to improve beneficial traits in BCAs. Integration with digital technologies, including artificial intelligence (AI), geographic information systems (GIS), and drone-based delivery, holds promise for precision deployment and real-time disease forecasting.

Together, these advances highlight a transformative path forward. With continued research and better field implementation strategies, BCAs are set to become a cornerstone of climate-resilient, consumer-safe, and ecologically balanced vegetable disease management systems.

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