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Efficacy of Bio-Control Agents on the Management of Damping-Off Disease in Tomato

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Damping-off is one of the most economically significant soil-borne diseases affecting tomato (*Solanum lycopersicum* L.) production worldwide, causing substantial losses at both pre-emergence and post-emergence seedling stages. The disease is attributed to a complex of pathogenic fungi and oomycetes, principally *Pythium* spp., *Rhizoctonia solani* Kühn, *Fusarium* spp., and *Phytophthora* spp., which persist in soil and infect susceptible host tissue under favourable environmental conditions. Typical disease manifestations include seed rot prior to germination, collapse of emerging seedlings at the soil surface, and progressive root and hypocotyl decay following emergence, collectively resulting in significant reductions in stand establishment and crop yield (Agrios, 2005; Vallad & Goodman, 2004).

Historically, chemical fungicides such as metalaxyl, captan, and thiram have been the primary means of managing damping-off. However, increasing concerns regarding pesticide residues, development of fungicide-resistant pathogen populations, disruption of non-target soil microbiota, and heightened regulatory restrictions on agrochemical use have collectively intensified interest in alternative disease management strategies (Pal & McSpadden Gardener, 2006). In this context, biological control, which exploits naturally occurring antagonistic microorganisms to suppress plant pathogens, has emerged as a scientifically credible and environmentally sustainable approach. This review synthesises current knowledge on the biological management of damping-off in tomato, with emphasis on the principal biocontrol agents employed, their modes of action, and the potential of integrated management frameworks to enhance disease suppression.

Causal Agents and Disease Epidemiology

The damping-off complex in tomato is polyphagous in nature, with multiple soilborne pathogens capable of acting individually or synergistically to cause disease. Pythium spp., classified as oomycetes rather than true fungi, are particularly destructive under conditions of high soil moisture and cool temperatures, primarily causing pre-emergence damping-off through rapid colonisation of germinating seeds. *Rhizoctonia solani*, a basidiomycete with a broad host range, produces characteristic hypocotyl lesions at or below the soil line, frequently causing post-emergence seedling collapse. *Fusarium* spp., notably *F. oxysporum* and *F. solani*, induce both damping-off and crown rot, with pathogenicity enhanced under warm and dry soil conditions. Phytophthora spp. present an additional oomycete threat, often associated with waterlogged soils in nursery environments (Menzies, 1970; Pythium: Agrios, 2005).

Environmental factors exert a profound influence on disease incidence and severity. Excessive soil moisture, poor drainage, high planting density, inadequate ventilation in nursery structures, and suboptimal sterilisation of growing media collectively create conditions conducive to pathogen proliferation and infection. Consequently, disease management strategies must address both pathogen suppression and the manipulation of environmental conditions to minimise host susceptibility.

Trichoderma spp. as Biocontrol Agents

Species of the genus *Trichoderma* (Hypocreales: Hypocreaceae) are among the most extensively researched and commercially deployed biocontrol fungi for the management of soil-borne plant pathogens. Their antagonistic efficacy against damping-off pathogens is attributable to a multiplicity of complementary mechanisms, which together render them highly effective under diverse soil conditions.

Mycoparasitism constitutes a primary mode of action, whereby *Trichoderma* hyphae actively recognise, coil around, and penetrate the hyphae of host pathogens, secreting a battery of cell wall-degrading enzymes including chitinases, glucanases, and proteases that facilitate parasitic colonisation and pathogen destruction (Harman et al., 2004). Concurrently, Trichoderma spp. produce a diverse array of volatile and non-volatile secondary metabolites with potent antifungal properties, including gliotoxin, gliovirin, harzianic acid, and various peptaibols, which inhibit pathogen growth and spore germination (Vinale et al., 2008).

Furthermore, Trichoderma spp. are highly competitive colonisers of the rhizosphere, effectively occupying ecological niches and depleting nutrients that would otherwise support pathogen proliferation. Beyond direct antagonism, these fungi stimulate plant immunity through the induction of systemic resistance, priming defence-related gene expression and the accumulation of pathogenesis-related proteins in tomato (Shoresh et al., 2010). Among the most widely documented species, Trichoderma viride and Trichoderma asperellum have been reported to significantly reduce damping-off incidence and improve seedling vigour in tomato nurseries when applied as seed treatments or soil drenches (Papavizas, 1985; Harman et al., 2004).

Plant Growth-Promoting Rhizobacteria

Plant growth-promoting rhizobacteria (PGPR), particularly *Pseudomonas fluorescens* and *Bacillus subtilis*, constitute another major category of biocontrol agents with demonstrated efficacy against damping-off pathogens in tomato. These bacteria colonise the rhizosphere and suppress pathogenic organisms through the production of a diverse arsenal of bioactive compounds. *Pseudomonas fluorescens* produces 2,4-diacetylphloroglucinol (DAPG), phenazines, pyoluteorin, and hydrogen cyanide, all of which exhibit broad-spectrum antimicrobial activity against oomycete and fungal pathogens (Haas & Défago, 2005). *Bacillus subtilis* and related species generate lipopeptide antibiotics, including iturin A, surfactin, and fengycin, which disrupt pathogen cell membranes and effectively inhibit spore germination and mycelial growth (Ongena & Jacques, 2008).

In addition to antibiotic production, PGPR elaborate siderophores that sequester iron in the rhizosphere, thereby creating conditions of iron limitation that constrain pathogen growth. Hydrolytic enzymes, including chitinases and proteases, further contribute to antagonism by degrading structural components of fungal cell walls. Beyond their biocontrol functions, PGPR enhance plant growth and resistance through multiple mechanisms: fixation and solubilisation of soil nutrients, production of phytohormones such as indole-3-acetic acid (IAA) and cytokinins, and stimulation of induced systemic resistance (ISR), which primes the tomato plant's immune system for more rapid and robust responses to subsequent pathogen challenge (van Loon et al., 1998; Lugtenberg & Kamilova, 2009).

Integrated Biological and Cultural Management Approaches

While individual biocontrol agents demonstrate significant efficacy, integration of biological control with complementary cultural and physical practices offers considerably greater and more durable disease suppression. The incorporation of organic amendments, such as composted plant residues, farmyard manure, or biochar, into nursery growing media enhances soil microbial diversity and activity, promotes the establishment of suppressive soil communities, and indirectly reduces pathogen propagule density (Hoitink & Boehm, 1999). Mature composts, in particular, are well-documented as carriers of diverse antagonistic microflora capable of suppressing Pythium and Rhizoctonia-incited damping-off.

Soil solarisation, which employs solar radiation to elevate soil temperatures to levels lethal or inhibitory to soilborne pathogens, provides a valuable complementary physical intervention that can be effectively combined with biocontrol agent inoculation to enhance suppressive capacity. The sequential application of solarisation followed by biocontrol agent introduction exploits the reduced pathogen load and disrupted competing microbial populations created by thermal treatment to facilitate more efficient colonisation and establishment of the introduced antagonists (Katan, 1981). Additionally, the adoption of sound cultural practices, including the use of pasteurised or sterilised potting media, regulation of irrigation to avoid waterlogging, maintenance of adequate plant spacing to ensure air circulation, and selection of disease-tolerant tomato cultivars, significantly reduces the environmental conditions that predispose seedlings to infection.

Efficacy of Biological Control Formulations

A substantial and growing body of research has demonstrated the high efficacy of biological control formulations under both controlled and field nursery conditions. Combined formulations incorporating *Trichoderma* spp. and *Pseudomonas fluorescens* have been reported to reduce damping-off incidence by 70 to 80 percent in tomato nurseries, representing performance levels comparable to or exceeding those achieved with conventional chemical fungicide applications (Whipps, 2001; Siddiqui & Shaukat, 2002). These agents confer multiple simultaneous benefits: direct suppression of pathogen populations through antagonistic mechanisms, stimulation of root architecture development and branching, enhancement of seedling dry weight and vigour index, and improvement of overall crop establishment rates.

The consistency of biocontrol efficacy under field conditions, however, remains a subject of ongoing research. Performance variability associated with fluctuating soil temperature and moisture regimes, differences in native soil microbial community composition, and suboptimal formulation storage and application methods represents a continuing challenge for the widespread commercial adoption of biocontrol strategies. Advances in formulation technology, including encapsulation, wettable powder, and granular delivery systems, are progressively addressing these limitations and improving shelf-life and field performance of biocontrol products.

Conclusion

Biological management represents an ecologically sound, scientifically validated, and practically viable strategy for the control of damping-off in tomato seedling production. The judicious deployment of biocontrol agents, notably *Trichoderma* spp. and plant growth-promoting rhizobacteria, exploits diverse and complementary mechanisms of pathogen suppression while simultaneously enhancing plant growth and systemic immunity. The integration of these agents within broader disease management frameworks, encompassing soil amendment, solarisation, and adherence to sound cultural practices, offers the prospect of durable and economically effective disease control without the environmental and health costs associated with chemical fungicide dependency. Future research priorities should include the elucidation of synergistic interactions among combined biocontrol consortia, the development of stable and efficacious formulations suited to diverse soil and climatic conditions, and the identification of reliable molecular markers for monitoring biocontrol agent persistence and activity in the rhizosphere. Continued progress in these areas will be essential to realising the full potential of biological management as a cornerstone of sustainable and integrated tomato production systems.

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