

Biological Control of Soil-Borne Pathogens

Tharringwon Marchang Ningshen^{1*}, Pranab Dutta², Madhusmita Mahanta¹, Lydia Vanlaltani¹, Harshit Singh¹

¹College of Post Graduate Studies in Agricultural Sciences, Central Agricultural University (Imphal), Umiam, Meghalaya (793103), India

²College of Agriculture, Central Agricultural University (Imphal), Kyrdemkulai, Meghalaya (793104), India

Abstract

Modern agricultural methods are currently replacing conventional methods worldwide in order to increase crop yields. The use of chemical fertilizers and pesticides has significantly increased in the agriculture sector for the same reason. However, the environment and human health are being severely jeopardized by the usage of these synthetic substances. One of the interesting solutions that researchers are currently looking for is biological control. It protects crops from the harmful effects of numerous plant infections while also protecting human health and the environment. Many crops suffer severe diseases as a result of soilborne microorganisms because of the pathogen's close association with the soil they share common characteristics, which greatly affect both their ability to survive and spread disease. Controlling soil-borne infections is a well-known challenge. Since soil-borne and root diseases of important crop plants cannot be controlled by crop rotation, resistant plant varieties or pesticide application, one of the best options for managing soil-borne diseases is the use of environmentally friendly biocontrol agents in greenhouses and the field.

Keywords Biological control, chemical pesticides, disease, soilborne

Introduction

Controlling soil-borne pathogens is essential to eliminate diseases of plants and conserve food, feed, and fiber in terms of both quantity and quality that producers generate worldwide. Numerous bacteria and nematodes, and fungi like *Aphanomyces euteiches*, *Colletotrichum falcatum*, *Criconemella xenoplax*, *Fusarium oxysporum*, *Thielaviopsis basicola*, *Phytophthora cinnamomi*, *Gaeumannomyces graminis var. tritici*, *Phytophthora infestans*, *Pythium splendens*, *Pythium ultimum*, *Plasmodiophora brassicae*, *Rhizoctonia solani*, *Streptomyces scabies*, *Ralstonia solanacearum*, *Heterodera avenae*, *Heterodera schachtii*, and *Meloidogyne spp.* are responsible for soil-borne diseases. (Weller *et al.*, 2002). Root rot, stem collar & crown rot, wilt, vascular wilt, damping off, soft rot, and other diseases are among the most typical

*Corresponding author's e-mail: tharringmcningshen@gmail.com

In: Current Trends in the Diagnosis and Management of Plant Diseases. (Eds.) Dutta, P., Upamanya, G.K., Pandey, A.K., 2024. Biotica Publications, Tripura, India.

diseases caused by soil-borne infections. If neglected, soil-borne illnesses have the potential to drastically lower crop production and destroy entire regions' agricultural industries (Strange *et al.*, 2005). To avoid, reduce, or manage soil-borne plant diseases, various strategies may be employed. Farmers frequently rely largely on chemical pesticides and fertilizers in addition to sound horticultural and agronomic methods. Over the past century, crop yield and quality have increased and this has been largely attributed to the use of such agricultural inputs. However, fear-mongering by certain opponents of pesticides and environmental degradation from excessive and improper use of agrochemicals have prompted significant shifts in public perceptions toward pesticide usage in agriculture. Chemical pesticides are now subject to stringent regulations, and political pressure is mounting to remove the most hazardous compounds from trade. In order to combat pests and diseases, several researchers studying pest management have concentrated on creating substitutes for synthetic chemicals. The so-called biological controls are one type of alternative. (Pal and Spadden, 2006)

There are several biological controls that can be used; however, in order for them to be developed further and used effectively, A more thorough understanding of the complex interactions between people, plants, and the environment is required. Although the importance of environmentally friendly pest control for sustainable agriculture is well established, not much is being changed at the field level. Among these pests include nematodes, rodents, weeds, insects, mites, fungi, and bacteria. This environmentally friendly approach to pest management emphasizes the use of biological control more.

Biological control of plant pathogens is now acknowledged as an essential practice in sustainable agriculture since it focuses on the management of a natural resource, specifically, certain rhizosphere organisms that are common ecosystem components and are known to develop antagonistic activities against harmful organisms like nematodes, fungi, and bacteria. (Azcón-Aguilar and Barea., 1997). Therefore, we may be able to alter the soil environment to promote efficient biocontrol or improve current biocontrol strategies by understanding how the pathogen and bio-control agent interact to biologically control plant diseases (Chaur, 1998). Consequently, the concept of biological control over plant diseases has become more inclusive, as seen by several accounts, and involves multiple mechanisms.

1. Mechanism of Biocontrol Agents

Upon encountering other species, pathogens become agitated by their presence and actions. Here we assert that depending on the uniqueness of the interactions and the degree of interspecies contact, various antagonizing processes appear along a directionality spectrum (Table I). A high degree of pathogen selectivity caused by the BCA(s) mechanism or physical contact both lead to direct antagonistic associations. This paradigm states that hyperparasitism by obligatory parasites of a plant pathogen would be the most direct form of antagonism because no other organism's actions would

be necessary to have a suppressive effect.

Conversely, activities that do not require the BCA(s) to identify or target a pathogen give rise to indirect antagonists. The most indirect kind of host resistance is caused by non-pathogenic BCAs stimulating host defense pathways in plants. The majority of pathogen suppression mechanisms that have been described, however, will be impacted by other species relative abundance besides the pathogen found in the environment. Despite the fact that many research have attempted to ascertain the importance of specific biocontrol mechanisms for specific pathosystems, it's likely that all of the mechanisms listed below are functioning in some capacity in ecosystems that are both natural and regulated. Additionally, the most effective BCAs discovered to date seem to inhibit infections in a variety of ways. For example, the host defense mechanism may be stimulated by pseudomonads that produce the antibiotic 2,4-diacetylphloroglucinol (DAPG) (Iavicoli *et al.*, 2003). Moreover, by competing for organic nutrients, DAPG-producing plants

Table 1: Types of biological control causing interspecies antagonism (Source- Pal and Gardener, 2006).

Type	Mechanism	Examples
Direct antagonism	Hyperparasitism/ predation	<i>Lytic/ some nonlytic mycovirus</i> <i>Ampelomyces quisqualis</i> <i>Lysobacter enzymogenes</i> <i>Pasteuria penetrans</i> <i>Trichoderma virens</i> <i>Trichoderma lignorum</i>
Mixed-path antagonism	Antibiotics	2,4-diacetylphloroglucinol Phenazines Cyclic lipopeptides
	Lytic enzymes	Chitinases Glucanases Proteases
	Unregulated waste products	Ammonia Carbon dioxide Hydrogen cyanide
	Physical/chemical interference	Blockage of soil pores Germination signals consumption Molecular cross-talk confused
Indirect antagonism	Competition	Exudates/leachates consumption Siderophore scavenging Physical niche occupation
	Induction of host resistance	Contact with fungal cell walls Detection of pathogen-associated molecular patterns, Phytohormone-mediated induction

may be able to restrict the action of pathogens in the rhizosphere of wheat. Another trait that can help them further reduce pathogen activity is their capacity to actively penetrate roots (Raaijmakers and Weller, 2001).

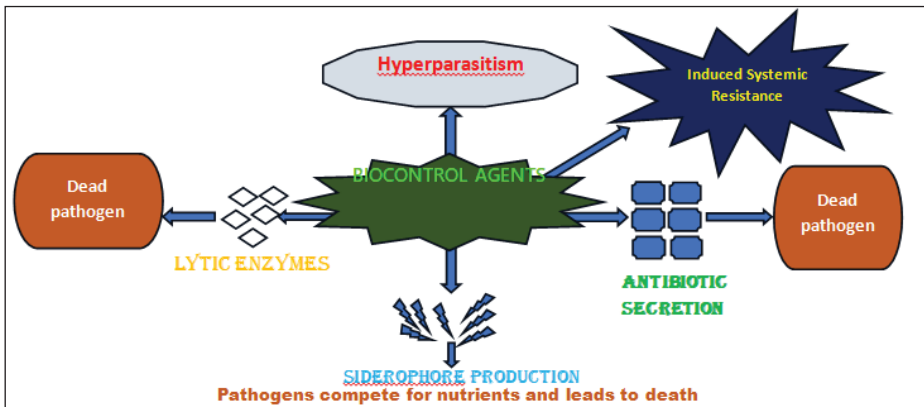


Figure 1: Mechanism of biocontrol agents

2. Hyperparasitism

In hyperparasitism, a particular BCA destroys the pathogen or its propagules by directly targeting the pathogen. Predators, obligatory bacterial pathogens, facultative parasites, and hypoviruses are the four primary categories of hyperparasites. *Pasteuria penetrans* is one obligatory bacterial pathogen of root-knot nematodes that has been employed as a BCA. The virus that infects the fungus *Cryphonectria parasitica*, which causes chestnut blight, is a well-known example. This virus causes a condition called hypovirulence, which lowers the pathogen's capacity to cause illness.

The phenomenon has controlled the chestnut blight in a number of areas (Milgroom and Cortesi, 2004). However, the way the virus, fungus, tree, and environment interact determines whether hypovirulence is successful or not. Plant diseases can be parasitized by numerous fungi; some target sclerotia (e.g. *Coniothyrium minitans*), while some focus on live hyphae (e.g. *Pythium oligandrum*). Also, several hyperparasites might target the same fungal pathogen. Fungi that can parasitize disease caused by powdery mildew include *Acremonium alternatum*, *Acrodontium crateriforme*, *Ampelomyces quisqualis*, *Cladosporium oxysporum*, and *Gliocladium virens* (Kiss, 2003).

3. Suppression mediated by antibiotics.

Antibiotics are microbial poisons that, in low concentrations have the ability to poison or kill other microbes. Most microorganisms both generate and exude at least one antibiotic-active chemical. *In vitro* and/or *in vivo* studies have demonstrated the exceptional efficacy of certain antibiotics generated by microorganisms in inhibiting the growth of plant pathogens and diseases. Table 2 provides instances of antibiotics that have been implicated in the reduction of plant pathogens.

Table 2: Antibiotics produced by various pathogens (Pal and Gardener, 2006)

Antibiotic	Source	Target pathogen	Disease	Reference
2,4-diacetyl phloroglucinol	<i>Pseudomonas putida</i>	<i>Colletotrichum falcatum</i>	Red rot of sugarcane	Hassan <i>et al.</i> (2011)
Bacillomycin, fengycin	<i>Bacillus amyloliquefaciens</i> FZB42	<i>Fusarium oxysporum</i>	Wilt	Koumoutsis <i>et al.</i> (2004)
Xanthobaccin A	<i>Lyso bacter sp. strain</i> SB-K88	<i>Aphanomyces cochlitioides</i>	Damping off	Islam <i>et al.</i> (2005)
Gliotoxin	<i>Trichoderma virens</i>	<i>Rhizoctonia solani</i>	Root rots	Wilhite <i>et al.</i> (2001)
Mycosubtilin	<i>B. subtilis</i> BBG100	<i>Pythium aphanidermatum</i>	Damping off	Leclere <i>et al.</i> (2005)
Surfactins, Iturins, Kurstakin, Fengycin	<i>B. amyloliquefaciens</i>	<i>Phaseolus vulgaris</i> L.	Charcoal root rot	Sabaté <i>et al.</i> (2017)
Pyocyanin	<i>Pseudomonas aeruginosa</i>	<i>Fusarium oxysporum f.sp. ciceris</i> , <i>Pythium ultimum</i>	Wilt of chickpea, Damping off	Jayaseelan <i>et al.</i> (2014)
Phenazine-1 carboxylic acid	<i>Pseudomonas fluorescens</i> and <i>P. aureofaciens</i> , <i>P. chlororaphis</i>	<i>Gaeumannomyces graminis var. tritici</i>	Take all	Labuschagne <i>et al.</i> (2010)
Mycobacillin	<i>B. subtilis</i>	<i>Phytophthora cactorum</i> , <i>Sclerotium cepivorum</i> , <i>Fusarium oxysporum</i> , <i>Rhizoctonia solani</i> , <i>Alternaria carthami</i> , <i>Phytophthora capsici</i>	Crown rot, White rot, Fusarium wilt, Root and stem rots, Leaf blight	Castillo <i>et al.</i> (2013)

Antibiotics are created *in vitro* by a variety of biocontrol agents; the amount of these compounds that are effective is hard to determine due to the small amounts produced in contrast to other organic compounds in the phytosphere that are less dangerous (Thomashow *et al.*, 2002). Additionally, even though methods for figuring out when and where biocontrol agents might produce antibiotics have been established (Notz *et al.*, 2001), the diverse distribution of plant-associated bacteria and possible infection regions makes it difficult to detect expression in the infection court. There have been a few cases when one or more of the genes that produce the antibiotics have been altered, it has been demonstrated how important the synthesis of antibiotics by biocontrol microorganisms is. For instance, it has been demonstrated that in comparison to their wild-type and complemented mutant counterparts, mutant strains lacking phenazines (Thomashow and Weller, 1988) or phloroglucinols (Keel *et al.*, 1992; Fenton *et al.*, 1992) are far less effective at suppressing soilborne root diseases, yet they are equally capable of colonizing the rhizosphere.

It is known that a number of biocontrol strains produce several antibiotics that have the ability to suppress one or more infections. *Bacillus cereus* strain UW85, for example, has been demonstrated to produce zwittermycin (Silo-Suh *et al.*, 1994) and kanosamine (Milner *et al.*, 1996). Multiple antibiotic production undoubtedly aids in suppressing several different microbial rivals, some of which may be plant pathogens. Biological control will likely be improved by the development of many classes of antibiotics that inhibit certain diseases in different ways.

4. Lytic enzymes and other microbiological byproducts

Numerous microorganisms release and excrete various compounds that could prevent infections from growing or functioning. Many bacteria manufacture and release lytic enzymes that can hydrolyze a wide variety of polymeric materials, such as proteins, chitin, cellulose, hemicellulose, and DNA. Plant pathogen activity may sometimes be directly reduced by the development and secretion of these enzymes by certain microbes. For instance, chitinase expression proved to be a mediator of *Serratia marcescens*' control over *Sclerotium rolfii* (Ordentlich *et al.*, 1988). Additionally, Cellulases, β -1,3 glucanases, and chitinases are examples of lytic extracellular enzymes that pseudomonads can generate and that are important in biocontrol activity by breaking down cell wall components like glucan, chitin, and glucosidic bridges.

For instance, *Pseudomonas* sp. produces hydrolytic enzymes that stimulate chickpea development and Additionally, has antifungal properties *in vitro* against *Pythium aphanidermatum* and *Rhizoctonia solani* (Sindhu and Dadarwal, 2001). Palumbo *et al.* (2005) state that β -1,3-glucanase is essential to *Lysobacter* strain C3's biocontrol activity. These enzymes mostly break down plant remnants and inanimate organic debris, while they may also cause stress to living organisms and/or lyse their

cell walls. Some might help reduce disease indirectly. For instance, it is commonly recognized that oligosaccharides derived from fungal cell walls have the ability to significantly boost the defenses of plant hosts. Chitinase produced by *Streptomyces* sp., *Paenibacillus* sp., and *Serratia marcescens* has been shown to inhibit *Sclerotium rolfsii*, *Botrytis cinerea*, and *Fusarium oxysporum* f. sp. *cucumerinum*. Similarly, *Fusarium oxysporum* f. sp. *radicis-lycopersici* cannot cause tomato root rot when chitosan is added to the plant growth substrate. It has been observed that β -1,3-glucanase produced by *Actinoplanes philippinensis* and *Micromonospora chalybeata* hydrolyzes *Pythium aphanidermatum* in cucumbers (El-Tarabily, 2006).

Various microbial metabolites might potentially play a role in suppressing pathogens. The cytochrome oxidase pathway is efficiently inhibited by hydrogen cyanide (HCN), which is extremely hazardous to all aerobic microbes at picomolar doses. Antibiotics, siderophores, and HCN are produced by *P. fluorescens* CHA0; but, HCN production seems to be the main factor in suppressing *Thielaviopsis basicola*-caused tobacco black rot (Voisard *et al.*, 1989). According to Howell *et al.* (1988), cotton's resistance to damping-off caused by *Pythium ultimum* is suppressed by volatile compounds such as ammonia produced by *Enterobacter cloacae*. Little is known about the kinds and quantities of chemicals produced in natural systems with and without plant disease, despite the fact that it is clear that biocontrol microorganisms can release a wide range of compounds into their environment.

5. Competition

From a microbiological point of view, the surfaces and soils of living plants are frequently nutrient-limited. For a bacteria to colonize the phytosphere, it must effectively compete for the available resources. Exudates, leachates, and senesced tissue are examples of nutrients that are provided by the host and present on the surfaces of plants. Moreover, soil and the waste products of other organisms, such as insects (like aphid honeydew on leaf surfaces), can provide nutrients. Soilborne pathogens such as *Fusarium* and *Pythium* species that spread through mycelial contact are typically more susceptible to competition from other soil and plant-associated microbes than those that germinate directly on plant surfaces and spread through appressoria and infection pegs. Competition for rare but essential micronutrients, like as iron, has also been investigated as a biocontrol basis. The rhizosphere is extremely iron-deficient, depending on the soil's pH. Extremely oxidized and aerated soil contains ferric iron (Lindsay, 1979), which is insoluble in water (pH 7.4) and can be detected in concentrations as low as 10^{-1} M. Usually, microorganisms need concentrations closer to 10^{-6} M, and this concentration is not enough to keep them growing. To survive in such conditions, organisms have been found to produce siderophores, which are iron-binding ligands with a high affinity for sequestering iron from the microenvironment.

The majority of microbes generate siderophores, which can be either hydroxamate or catechol-type (Neilands, 1981). The importance of siderophore

production as a biological control mechanism for *Erwinia carotovora* was originally demonstrated by Kloepper *et al.* (1980) utilizing a variety of plant-growth-promoting *Pseudomonas fluorescens* strains, such as A1, BK1, TL3B1 and B10. In *In vitro*, condition Elad and Baker (1985) and Sneh *et al.* (1984) discovered a clear correlation between the production of siderophores and fluorescent pseudomonads' capacity to stop *F. oxysporum* chlamydospore germination. Similar to how antibiotics work, mutants that are unable to produce certain siderophores, like pyoverdine, have a decreased ability to control various plant diseases (Keel *et al.*, 1989, Loper and Buyer, 1991).

6. Resistance induction in the host

It is a crucial plant defense mechanism in which specific rhizosphere-dwelling beneficial microorganisms or bacteria that promote plant growth, target the whole plant for better defense against a variety of diseases (Handelsman and Stabb, 1996). A beneficial microbial population can induce ISR by producing unique elicitors and microbe-associated molecular patterns (MAMPs) (Pieterse *et al.*, 2014).

The development of induced resistance, both locally at the site of induction and systemically in other plant components that are geographically far from the inducer, is referred to as "induced resistance" (ISR). Plant hormones like ethylene and jasmonic acid, which are interrelated signaling pathways, are major regulators of induced resistance (Pineda *et al.*, 2010). Numerous root-associated microorganisms, including as *Pseudomonas*, *Bacillus*, *Trichoderma*, and mycorrhizal species, stimulate the plant immune system to create defense chemicals like chitinase, peroxidase, and pathogenesis-related proteins. (Contreras-Cornejo *et al.*, 2009; Jung *et al.*, 2012; Cameron *et al.*, 2013; Zamioudis *et al.*, 2013). Phytopathologists have explored the mechanisms and factors of induced resistance caused by biological control agents and non-pathogenic microbes (Table 3). The production of pathogenesis-related (PR) proteins typically coexists with the first of these pathways, which is called salicylic acid (SA)-mediated systemic acquired resistance (SAR). A common byproduct of pathogen infection is the production of salicylic acid (SA). Some of the enzymes found in these PR proteins have the ability to lyse invasive cells directly, strengthen cell wall borders to fend off infections, or cause localized cell death. After certain nonpathogenic rhizobacteria are applied, ethylene and/or jasmonic acid (JA) are created. This results in a second phenotype that was first identified as induced systemic resistance (ISR). The defensive pathways that rely on SA and JA can be mutually antagonistic, which is an interesting finding. Many bacterial diseases take advantage of this trait to overcome the SAR. As an illustration, pathogenic strains of *Pseudomonas syringae* overcome the SA-mediated pathway by producing coronatine, which is comparable to JA (He *et al.*, 2004).

It is commonly known that some biocontrol strains of *Pseudomonas* and *Trichoderma* greatly strengthen their plant hosts' defences (Harman, 2004).

Table 3: Biocontrol agents that work by inducing resistance. (Fontana *et al.*, 2021)

Biocontrol agents	Host	Pathogens Target	References
<i>Phialomyces macrosporus</i>	<i>Coffea arabica</i>	<i>Colletotrichum gloeosporioides</i>	Rodríguez <i>et al.</i> , 2016
<i>Fusarium solani sensu lato</i>	S. <i>lycopersicum</i>	<i>Fusarium oxysporum f. sp. radicis-lycopersici</i> , <i>Septoria lycopersici</i>	Kavroulakis <i>et al.</i> , 2007
<i>Trichoderma harzianum</i>	S. <i>lycopersicum</i>	<i>Alternaria solani</i> , <i>Phytophthora infestans</i> .	Martínez-Medina <i>et al.</i> , 2013
<i>T. virens</i>	S. <i>lycopersicum</i>	<i>Fusarium oxysporum f. sp. lycopersici</i>	Jogaiah <i>et al.</i> , 2018
<i>T. harzianum</i> , <i>T. asperellum</i> , <i>T. atroviride</i> , <i>T. strigosum</i> and <i>T. longibrachiatum</i>	<i>Cucumis sativus</i>	<i>Colletotrichum lagenarium</i>	Da Silva <i>et al.</i> , 2011
<i>Piriformospora indica</i>	<i>Solanum lycopersicum</i>	Nematode <i>Meloidogyne incognita</i>	Varkey <i>et al.</i> , 2018
<i>Penicillium brefeldianum</i>	<i>Cucumis melo</i>	<i>Meloidogyne incognita</i>	Miao <i>et al.</i> , 2019
<i>Fusarium oxysporum sensu lato</i>	<i>Arabidopsis thaliana</i>	<i>Meloidogyne incognita</i>	Martinuz <i>et al.</i> , 2015
<i>T. harzianum</i>	<i>Glycine max</i>	<i>Pratylenchus brachyurus</i>	Kath <i>et al.</i> , 2017
<i>Trichoderma atroviride</i>	<i>Solanum lycopersicum</i>	<i>Meloidogyne javanica</i>	De Medeiros <i>et al.</i> , 2017
<i>T. asperellum</i>	<i>Cucumis sativus</i>	Bacteria <i>Pseudomonas syringae pv. lachrymans</i>	Yedidia <i>et al.</i> , 2003 Yedidia <i>et al.</i> , 2003
<i>T. asperellum</i>	<i>Solanum lycopersicum</i>	<i>Ralstonia solanacearum</i>	Konappa <i>et al.</i> , 2018

It has been demonstrated that plant-growth-promoting rhizobacteria (PGPR) inoculations are successful in managing a range of diseases caused by different pathogens, including bacterial wilt (*Erwinia tracheiphila*), angular leaf spot (*Pseudomonas syringae* pv. *lachrymans*), and anthracnose (*Colletotrichum lagenarium*). A range of chemical elicitors of SAR and ISR, including lipopolysaccharides, salicylic acid, siderophores, 2,3-butanediol, and other volatile chemicals, may be produced by the PGPR strains upon inoculation (Ongena *et al.*, 2004; Ryu *et al.*, 2004).

7. Biocontrol agent formulation and application techniques

One key strategy for a biocontrol agent's commercial success against plant pathogens is formulation. A designed microbial product is made by combining substances to enhance the survival and efficiency of one or more agents of biological regulation (consortium) (Schisler *et al.*, 2004). As agents of biological control (BCAs) or biopesticides, a variety of microorganisms are now being investigated and employed. *Bacillus species*, *Ampelomyces quisqualis*, *Trichoderma species*, *Pseudomonas fluorescense*, *Agrobacterium radiobacter*, *nonpathogenic Fusarium*, *Coniothyrium*, and *atoxigenic Aspergillus niger* are examples of well-known BCAs (Singh, 2006; Keswani *et al.*, 2014; Mishra *et al.*, 2015).

The long shelf life and consistent, dependable efficacy of biological control are the primary barriers to its commercialization and competitiveness with chemical fungicides. The scientific development of biocontrol agent composition can address both issues. Formulations have several advantages, including increased efficacy, extended shelf life, ease of handling, safety, lower manufacturing costs, and compatibility with agricultural practices (Spadaro and Gullino, 2005). The purpose of usage will decide the kind of formulation that is necessary. A liquid formulation would be appropriate for use in soil less cultures, where delivering the inoculant *via* a drip irrigation system would be the most practical approach. For root dips or sprays, a wettable powder would be more acceptable than a granular substance. *C. minitans* is applied using one of two methods: either soil application to reduce the sclerotial inoculum-potential or spore sprays onto diseased plants or agricultural debris to sterilize the crop (De vrije *et al.*, 2001). A biofungicide typically contains a large number of additives added for different objectives, including food sources, coating compounds, binders, dispersants, buffering systems, lubricants, activators, bulking additives, membrane stabilizers, growth and contaminant suppressants, carriers, and diluents (Paau, 1998). According to Spadaro and Gullino (2005), these include maintaining antagonist viability, monitoring bulk for handling and distribution, enhancing BCA action, and stopping the spread of possible contaminants.

8. Conservation and Management

Beneficial antagonist conservation can be accomplished in two ways: either by maintaining the current population of microbes that either outcompete

or attack pathogens, or by improving the environmental factors that support their reproduction and survival over dangerous species. Additionally, soil amendments, the addition of organic matter, and avoiding actions that could harm the organisms such as applying fungicides to the soil can improve the soil habitat for desired species (Van Driesche and Bellows, 1996). The application of biocontrol by augmentation, which involves inoculating soils or plants with certain beneficial microbes based on mass-culturing antagonistic species, is suitable in situations when natural enemy populations are scarce or exist in unintended locales. Augmentation is used to change their distribution or boost their population. According to Andrews (1992) and Cook (1993), “introduction” in the context of plant pathology refers to the process of introducing hostile bacteria into the system. These microorganisms are usually indigenous to the region and are not imported from elsewhere.

Conclusion

Compared to chemical control, one sustainable way to manage plant diseases and lower pathogenic activity is through biocontrol. Synthetic pesticides used for chemical pathogen control contaminate soil, threaten the diversity of life on Earth and have detrimental effects on all living things, including people. Microbial biocontrol agent registrations are sharply rising on a global scale. The increasing use of biocontrol agents is being facilitated by modifications to national legislation as well as the creation of new policies and management frameworks intended to cut down the usage of chemicals. Nevertheless, researchers around the globe have received assistance in finding novel biocontrol agents to strengthen their entry into the market. Considering all of the advantages it provides, increasing interest and growing public concerns, biological control is without a doubt one of the many safe and successful ways to use natural opponents to manage dangerous species.

References

- Abd Dababat, E. F. A., Alexander Sikora, R. 2007. Induced resistance by the mutualistic endophyte, *Fusarium oxysporum* strain 162, toward *Meloidogyne incognita* on tomato. *Biocontrol Science and Technology*. 17(9), 969-975.
- Andrews, J. H., 1992. Biological control in the phyllosphere. *Annual review of phytopathology*, 30(1), 603-635.
- Azcón-Aguilar, C., Barea, J. M. 1997. Arbuscular mycorrhizas and biological control of soil-borne plant pathogens an overview of the mechanisms involved. *Mycorrhiza*. 6, 457-464.
- Boro, M., Sannyasi, S., Chettri, D., Verma, A. K. 2022. Microorganisms in biological control strategies to manage microbial plant pathogens: a review. *Archives of microbiology*. 204(11), 666.
- Cameron, D. D., Neal, A. L., Van Wees, S. C., Ton, J. 2013. Mycorrhiza-induced resistance: more than the sum of its parts. *Trends in Plant Science* 18(10), 539-545

- Castillo, H. F., Reyes, C. F., Morales, G. G., Herrera R. R., Aguilar, C. 2013. Biological control of root pathogens by plant-growth promoting *Bacillus* spp. *Weed and pest control-conventional and new challenges*, 79-103. DOI: <https://doi.org/10.5772/54229>
- Chaur T. 1998. General mechanisms of action of microbial biocontrol agents. *Plant Pathology Bulletin*. 7(4), 155- 166. ISSN/ISBN: 1021-9544. Accession: 003149554
- Chowdappa, P., Kumar, S. M., Lakshmi, M. J., Upreti, K. K. 2013. Growth stimulation and induction of systemic resistance in tomato against early and late blight by *Bacillus subtilis* OTPB1 or *Trichoderma harzianum* OTPB3. *Biological control*, 65(1), 109-117.
- Contreras-Cornejo, H. A., Macias-Rodriguez, L., Cortes-Penagos, C., Lopez-Bucio, J. 2009 *Trichoderma virens*, a plant beneficial fungus, enhances biomass production and promotes lateral root growth through an auxin-dependent mechanism in Arabidopsis. *Plant Physiology*. 149(3), 1579-1592
- Cook, R. J. 1993. Making greater use of introduced microorganisms for biological control of plant pathogens. *Annual Review of Phytopathology*. 31(1), 53-80
- De Vrije, T., Antoine, N., Buitelaar, R. M., Bruckner, S., Dissevelt, M., Durand, A., Gerlagh, M., Jones, E. E., Luth, P., Oostra, J., Ravensberg, W. J., Renaud, R., Rinzema, A., Weber, F. J., Whipps, J. M. 2001. The fungal biocontrol agent *Coniothyrium minitans*: production by solid-state fermentation, application and marketing. *Applied Microbiology and Biotechnology*. 56, 58-68.
- Elad, Y., and Baker, R. 1985. Influence of trace amounts of cations and siderophore-producing pseudomonads on chlamydospore germination of *Fusarium oxysporum*. *Ecological Epidemiology*. 75(9), 1047-1052
- El-Tarabily, K. A. 2006. Rhizosphere-competent isolates of streptomycete and non-streptomycete actinomycetes capable of producing cell-wall degrading enzymes to control *Pythium aphanidermatum* damping-off disease of cucumber. *Canadian Journal of Botany*. 84(2), 211-222
- Fenton, A.M., Stephens, P. M., Crowley, J., O'Callaghan, M., O'Gara, F. 1992. Exploitation of gene(s) involved in 2,4-diacetyl phloroglucinol biosynthesis to confer a new biocontrol capability to a *Pseudomonas* strain. *Applied and Environmental Microbiology*. 58(12), 3873-3878
- Fontana, D. C., de Paula, S., Torres, A. G., de Souza, V. H. M., Pascholati, S. F., Schmidt, D., Dourado Neto, D. 2021. Endophytic fungi: Biological control and induced resistance to phytopathogens and abiotic stresses. *Pathogens*, 10(5), 570.
- Handelsman, J., and Stabb, E. V. 1996. Biocontrol of soilborne plant pathogens. *The Plant Cell*. 8(10), 1855-1869
- Harman, G. E., Howell, C. R., Vitarbo, A., Chet, I., and Lorito, M. 2004. *Trichoderma* species - opportunistic, avirulent plant symbionts.

- Nature Review Microbiology*. 2(1), 43-56.
- Hassan, M. N., Afghan, S., Hafeez, F.Y. 2011. Biological control of red rot in sugarcane by native pyoluteorin-producing *Pseudomonas putida* strain NH-50 under field conditions and its potential modes of action. *Pest Management Science* 67(9), 1147-1154
- He, P., Chintamanani, S., Chen, Z., Zhu, L., Kunkel, B. N., Alfano, J. R., Tang, X., and Zhou, J. M. 2004. Activation of a COI1-dependent pathway in Arabidopsis by *Pseudomonas syringae* type III effectors and coronatine. *Plant Journal*. 37(4), 589-602.
- Howell, C. R., Beier, R. C., Stipanovic, R. D., 1988. Production of ammonia by *Enterobacter cloacae* and its possible role in the biological control of Pythium pre- emergence damping-off by the bacterium. *Phytopathology* 78(8),1075-1078.
- Iavicoli, A., Boutet, E., Buchala, A., Métraux, J. P., 2003. Induced systemic resistance in *Arabidopsis thaliana* in response to root inoculation with *Pseudomonas fluorescens* CHA0. *Molecular Plant-Microbe Interactions*.16(10), 851-858.
- Islam, M. T., Hashidoko, Y., Deora, A., Ito, T., Tahara, S., 2005. Suppression of damping-off disease in host plants by the rhizoplane bacterium *Lysobacter* sp. strain SB-K88 is linked to plant colonization and antibiosis against soilborne Peronosporomycetes. *Applied and Environmental Microbiology*. 71(7), 3786-3796.
- Jayaseelan, S., Ramaswamy, D., Dharmaraj, S., 2014. Pyocyanin: production, applications, challenges and new insights. *World Journal of Microbiology and Biotechnology*. 30(4), 1159-1168.
- Jogaiah, S., Abdelrahman, M., Tran, L. S. P., Ito S. I., 2018. Different Mechanisms of *Trichoderma virens*-mediated resistance in tomato against Fusarium Wilt involve the jasmonic and salicylic acid pathways. *Molecular Plant Pathology*.19(4), 870-882. doi: 10.1111/mpp.12571.
- Jung, S. C, Martinez-Medina, A., Lopez-Raez, J. A., Pozo, M. J., 2012. Mycorrhiza-induced resistance and priming of plant defenses. *Journal of chemical ecology*. 38, 651-664
- Kath, J., Dias-Arieira, C. R., Ferreira, J. C. A., Homiak, J. A., da Silva, C. R. D., Cardoso, C. R., 2017. Control of *Pratylenchus brachyurus* in Soybean with *Trichoderma* spp. and resistance inducers. *Journal of Phytopathology*. 165(11-12), 791-799. doi: 10.1111/jph.12619
- Kavroulakis, N., Ntougias, S., Zervakis, G. I., Ehaliotis, C., Haralampidis, K., Papadopoulou, K. K., 2007. Role of Ethylene in the Protection of Tomato Plants against Soil-Borne Fungal Pathogens Conferred by an Endophytic *Fusarium Solani* Strain. *Journal of Experimental Botany*. 58(14), 3853-3864.
- Keel, C. 1992. Suppression of root diseases by *Pseudomonas fluorescens* CHA0: importance of the bacterial secondary metabolite 2,4-diacetylphloroglucinol. *Molecular Plant-Microbe Interactions*. 5(1), 4-13.

- Keel, C., Voisard, C., Berling, C. H., Kahir, G., Defago, G. 1989. Iron sufficiency is a prerequisite for suppression of tobacco black root rot by *Pseudomonas fluorescens* strain CHA0 under gnotobiotic conditions. *Phytopathology* 79(5), 584-589.
- Keswani, C., Mishra, S., Sarma, B. K., Singh, S. P., Singh, H. B. 2014. Unraveling the efficient application of secondary metabolites of various *Trichoderma* spp *Applied Microbiology and Biotechnology*. 98, 533-544
- Kiss, L. 2003. A review of fungal antagonists of powdery mildews and their potential as biocontrol agents. *Pest Management Science*. 59(4), 475-483.
- Konappa, N., Krishnamurthy, S., Siddaiah, C. N., Ramachandrappa, N. S., Chowdappa, S., 2018. Evaluation of Biological Efficacy of *Trichoderma asperellum* against Tomato Bacterial Wilt Caused by *Ralstonia Solanacearum*. *Egyptian Journal of Biological Pest Control*. 28, 1-11. doi: 10.1186/s41938-018-0069-5.
- Koumoutsis, A., Chen, X. H., Henne, A., Liesegang, H., Gabriele, H., Franke, P., Vater, J., Borris, R., 2004. Structural and functional characterization of gene clusters directing nonribosomal synthesis of bioactive lipopeptides in *Bacillus amyloliquefaciens* strain FZB42. *Journal of Bacteriology*. 186, 1084-1096.
- Labuschagne, N., Pretorius, T., Idris, A. H. 2011. Plant growth promoting rhizobacteria as biocontrol agents against soil-borne plant diseases. *Plant growth and health promoting bacteria*, 211-230.
- Lahlali, R., Ezrari, S., Radouane, N., Kenfaoui, J., Esmaeel, Q., El Hamss, H., Barka, E. A., 2022. Biological control of plant pathogens: A global perspective. *Microorganisms*.10(3), 596.
- Leclere, V., Bechet, M., Adam, A., Guez, J. S., Wathélet, B., Ongena, M., Thonart, P., Gancel, F., Chollet-Imbert, M., Jacques, P. 2005. Mycosubtilin overproduction by *Bacillus subtilis* BBG100 enhances the organism's antagonistic and biocontrol activities. *Applied Environmental Microbiology*. 71(8), 4577-4584.
- Lindsay, W. L. 1979. *Chemical Equilibria in Soils*. John Wiley and Sons, New York. pp 449.
- Loper, J. E., Buyer, J. S. 1991. Siderophores in microbial interactions of plant surfaces. *Molecular Plant-Microbe Interaction*. 4(1), 5-13.
- Martínez-Medina, A., Fernández, I., Sánchez-Guzmán, M. J., Jung, S. C., Pascual, J. A., Pozo, M. J., 2013. Deciphering the hormonal signalling network behind the systemic resistance induced by *Trichoderma harzianum* in tomato. *Frontier Plant Science*. 4, 206. doi: 10.3389/fpls.2013.00206.
- Martinuz, A., Zewdu, G., Ludwig, N., Grundler, F., Sikora, R. A., Schouten, A., 2015. The application of *Arabidopsis thaliana* in studying tripartite interactions among plants, beneficial fungal endophytes and biotrophic plant-parasitic nematodes. *Planta*. 241, 1015-1025. doi: 10.1007/s00425-014-2237-5.

- Medeiros, H. A. D., Araújo Filho, J. V. D., Freitas, L. G. D., Castillo, P., Rubio, M. B., Hermosa, R., Monte, E. 2017. Tomato progeny inherit resistance to the nematode *Meloidogyne javanica* linked to plant growth induced by the biocontrol fungus *Trichoderma atroviride*. *Scientific reports*, 7(1), 40216.
- Miao, G. P., Han, J., Zhang, K. G., Wang, S. C., Wang, C. R., 2019. Protection of melon against Fusarium wilt-root knot nematode complex by endophytic fungi *Penicillium brefeldianum* HS-1. *Symbiosis*.77, 83–89. doi: 10.1007/s13199-018-0565-0.
- Milgroom, M. G., Cortesi, P., 2004. Biological control of chestnut blight with hypovirulence: a critical analysis. *Annual Review of Phytopathology*. 42(1), 311-338.
- Milner, J. L., Silo-Suh, L. A. U. R. A., Lee, J. C., He, H., Clardy, J., and Handelsman, J. O., 1996. Production of kanosamine by *Bacillus cereus* UW85. *Applied and environmental microbiology*. 62(8), 3061-3065.
- Mishra, S., Singh, A., Keswani, C., Saxena, A., Sarma, B. K., Singh, H. B., 2015. Harnessing plant-microbe interaction for enhanced protection against phytopathogens. *Plant microbes symbiosis: applied facets*. Springer, New Delhi. pp.111–125.DOI:10.1007/978-81-322-2068-8_5
- Neilands, J. B., 1981. Microbial iron compounds. *Annual Review of Biochemistry*. 50(1), 715-731.
- Notz, R., Maurhofer, M., Schnider-Keel, U., Duffy, B., Haas, D., and Defago, G., 2001. Biotic factors affecting expression of the 2,4-diacetylphloroglucinol biosynthesis gene *phlA* in *Pseudomonas fluorescens* biocontrol strain CHA0 in the rhizosphere. *Phytopathology*. 91(9), 873-881.
- Ongena, M., Duby, F., Rossignol, F., Fouconnier, M. L., Dommes, J., Thonart, P. 2004. Stimulation of the lipoxygenase pathway is associated with systemic resistance induced in bean by a nonpathogenic *Pseudomonas* strain. *Molecular Plant-Microbe Interaction*. 17(9), 1009-1018.
- Ordentlich, A., Elad, Y., Chet, I., 1988. The role of chitinase of *Serratia marcescens* in the biocontrol of *Sclerotium rolfsii*. *Phytopathology*. 78(1), 84-88.
- Paau, A. S., 1998. Formulation of beneficial organisms applied to soil. In *Formulation of Microbial Biopesticides: Beneficial microorganisms, nematodes and seed treatments*. pp. 235-254. Dordrecht: Springer Netherlands.
- Pal, K. K., Gardener, B. M., 2006. Biological Control of Plant Pathogens. *The Plant Health Instructor*, 2(5), 1117-1142. DOI: 10.1094/PHI-A-2006-1117-02.
- Palumbo, J. D., Yuen, G. Y., Jochum, C. C., Tatum, K., Kobayashi, D. Y., 2005. Mutagenesis of beta-1,3-glucanase genes in *Lysobacter enzymogenes* strain C3 results in reduced biological control activity

- toward *Bipolaris* leaf spot of tall fescue and *Pythium* damping-off of sugar beet. *Phytopathology* 95(6), 701-707.
- Pieterse, C. M., Zamioudis, C., Berendsen, R. L., Weller, D. M., Van Wees, S. C., Bakker, P. A. 2014. Induced systemic resistance by beneficial microbes. *Annual Review of Phytopathology*. 52(1), 347-375
- Pineda, A., Zheng, S. J., van Loon, J. J., Pieterse, C. M., Dicke, M., 2010. Helping plants to deal with insects: the role of beneficial soilborne microbes. *Trends in Plant Science*. 15(9), 507-514
- Raaijmakers, J. M., Weller, D. M. 2001. Exploiting genotypic diversity of 2, 4-diacetylphloroglucinol-producing *Pseudomonas* spp.: characterization of superior root-colonizing *P. fluorescens* strain Q8r1-96. *Applied and Environmental Microbiology*, 67(6), 2545-2554.
- Rodríguez, G. A. A., de Abreu, M. S., Pinto, F. A. M. F., Monteiro, A. C. A., Núñez, Á. M. P., de Resende, M. L. V., de Souza, J. T., de Medeiros, F. H. V. 2016. *Phialomyces Macrosporus* decreases anthracnose severity on coffee seedlings by competition for nutrients and induced resistance. *Biological Control*. 103, 119-128. doi: 10.1016/j.biocontrol.2016.08.009.
- Ryu, C. M., Farag, M. A., Hu, C. H., Reddy, M. S., Kloepper, J. W., and Pare, P. W., 2004. Bacterial volatiles induce systemic resistance in *Arabidopsis*. *Plant Physiology*. 134(3), 1017-1026.
- Sabaté, D. C., Brandan, C. P., Petroselli, G., Erra-Balsells, R., Audisio, M. C., 2017. Decrease in the incidence of charcoal root rot in common bean (*Phaseolus vulgaris* L.) by *Bacillus amyloliquefaciens* B14, a strain with PGPR properties. *Biological Control*. 113, 1-8.
- Schisler, D. A., Slininger, P. J., Behle, R. W., Jackson, M. A., 2004. Formulation of *Bacillus* sp. for biological control of plant diseases. *Phytopathology*. 94(11), 1267-1271
- Silo-Suh, L. A., Lethbridge, B. J., Raffel, S. J., He, H., Clardy, J., Handelsman, J., 1994 Biological activities of two fungistatic antibiotics produced by *Bacillus cereus* UW85. *Applied and Environmental Microbiology*. 60(6), 2023-2030
- Silva, V. N. D., Guzzo, S. D., Lucon, C. M. M., Harakava, R., 2011. Growth promotion and induction of anthracnose resistance by *Trichoderma* spp. in cucumber. *Brazilian Agricultural Research*. 46, 1609-1618.
- Sindhu, S. S., Dadarwal, K. R., 2001. Chitinolytic and cellulolytic *Pseudomonas* sp. antagonistic to fungal pathogens enhances nodulation by *Mesorhizobium* sp. Cicer in chickpea. *Microbiological research*. 156(4), 353-358.
- Singh, H. B., 2006. *Trichoderma*: A boon for biopesticides industry. *Journal of Mycology and Plant Pathology*. 36, 373-384
- Sneh, B., Dupler, M., Elad, Y., Baker, R., 1984. Chlamydo-spore germination of *Fusarium oxysporum* f. sp. *cucumerinum* as affected by fluorescent and lytic bacteria from *Fusarium* suppressive soils. *Phytopathology*. 74(9), 1115-1124.
- Spadaro, D., Gullino, M. L., 2005. Improving the efficacy of biocontrol agents

- against soilborne pathogens. *Crop protection*. 24(7), 601-613
- Strange, R. N., Scott, P. R., 2005. Plant disease: a threat to global food security. *Annual Review of Phytopathology*. 43(1), 83-116.
- Thomashow, L. S., Bonsall, R. F., Weller, D. M., 2002. Antibiotic production by soil and rhizosphere microbes *in situ*. In: Manual of environmental microbiology (Hurst, C. J., Crawford, R. L., Knudsen, G. R., McInerney, M. J. and Stezenbach, L. D., Eds.), second ed, pp. 638–647. ASM Press, Washington, DC.
- Van Driesche, R. G., Bellows, T. S. Jr., 1996. Methods for biological control of plant pathogens. *Biological control*. Springer, Boston. pp 235–256
- Varkey, S., Anith, K. N., Narayana, R., Aswini, S. A., 2018. Consortium of Rhizobacteria and Fungal Endophyte Suppress the Root-Knot Nematode Parasite in Tomato. *Rhizosphere*.5, 38–42. doi: 10.1016/j.rhisph.2017.11.005.
- Voisard, C., Keel, C., Haas, D., Defago, G., 1989. Cyanide production by *Pseudomonas fluorescens* helps suppress black root of tobacco under gnotobiotic conditions. *EMBO Journal*. 8,(2), 351-358.
- Weller, D. M., Raajmakers, J. M., Gardener, B. B. M., Thomashow, L. S., 2002. Microbial populations responsible for specific soil suppressiveness to plant pathogens. *Annual Review of Phytopathology*. 40(1), 309–348.
- Wilhite, S. E., Lunsden, R. D. Strancy, D. C., 2001. Peptide synthetase gene in *Trichoderma virens*. *Applied Environmental Microbiology*. 67(11), 5055-5062.
- Yedidia, I., Shores, M., Kerem, Z., Benhamou, N., Kapulnik, Y., Chet, I., 2003. Concomitant Induction of Systemic Resistance to *Pseudomonas syringae* Pv. *lachrymans* in Cucumber by *Trichoderma asperellum* (T-203) and Accumulation of Phytoalexins. *Applied Environmental Microbiology*. 69(12), 7343–7353. doi: 10.1128/AEM.69.12.7343-7353.200 .
- Zamioudis, C., Mastranesti, P., Dhonukshe, P., Blilou, I., Pieterse, C. M. J., 2013. Unraveling root developmental programs initiated by beneficial *Pseudomonas* spp. bacteria. *Plant Physiology*.162:304–318.