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Abstract

Globally, *Solanum lycopersicum* L. (tomatoes) is the second most widely grown vegetable. This crop is sensitive to over 200 diseases caused by a variety of phytopathogenic microorganisms, specifically, soil-borne fungi. The major fungal pathogen causing diseases in tomatoes are *Fusarium oxysporum* f. sp. *lycopersici*, *Botrytis cinerea*, *Verticillium dahliae*, *Sclerotium rolfsii*, *Colletotrichum* sp., *Alternaria* sp. *Rhizoctonia solani*, etc. Even though a wide range of chemical fungicides is now available to combat fungal diseases, the overuse of these chemicals has been shown to leave negative/adverse influences on the texture, yield and nutritive value of the fruits. In this regard, to manage the fungus-induced tomato diseases, plant growth-promoting (PGP) bacteria are one of the most environmentally friendly, effective, safe and economically sound solutions. A variety of beneficial soil microorganisms (BSMs) are currently being employed as soil or plant inoculants in several crop plants, including tomatoes, as biocontrol agents (BCAs). These BCAs also work as growth regulators, in addition to preventing fungal diseases. The current chapter discusses the application of beneficial and antagonistic BCAs, their effectiveness as well as bacterial-mediated mechanisms involved in the management of diseases in tomatoes. The specific mechanisms are antibiosis, competition, production of cellulolytic enzymes, cyanogenic compounds (HCN) and siderophore and induced systemic resistance (ISR). The ability of PGP rhizobacteria to antagonize a pathogen and suppress the disease through multiple pathways has been intensively studied to use them as effective BCAs. As a result, this chapter highlights a full explanation of various bacterial-mediated biocontrol mechanisms used by BCA. As environmental and health issues highlight the need to transition to a more sustainable agriculture system, the use of indigenous PGP rhizobacteria in plant disease prevention is gaining attraction. It's also recommended that using a bacterial consortium guarantees that BCA performs consistently in field settings.

Keywords (separated by '-')	*Solanum lycopersicum* - Tomatoes - Fungal diseases - Biocontrol agents (BCAs) - Antifungal metabolites

Chapter 15
Bacterial Inoculants for Control of Fungal Diseases in *Solanum lycopersicum* L. (Tomatoes): A Comprehensive Overview

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Abstract Globally, *Solanum lycopersicum* L. (tomatoes) is the second most widely grown vegetable. This crop is sensitive to over 200 diseases caused by a variety of phytopathogenic microorganisms, specifically, soil-borne fungi. The major fungal pathogen causing diseases in tomatoes are *Fusarium oxysporum* f. sp. *lycopersici*, *Botrytis cinerea*, *Verticillium dahliae*, *Sclerotium rolfsii*, *Colletotrichum* sp., *Alternaria* sp. *Rhizoctonia solani*, etc. Even though a wide range of chemical fungicides is now available to combat fungal diseases, the overuse of these chemicals has been shown to leave negative/adverse influences on the texture, yield and nutritive value of the fruits. In this regard, to manage the fungus-induced tomato diseases, plant growth-promoting (PGP) bacteria are one of the most environmentally friendly, effective, safe and economically sound solutions. A variety of beneficial soil microorganisms (BSMs) are currently being employed as soil or plant inoculants in several crop plants, including tomatoes, as biocontrol agents (BCAs). These BCAs also work as growth regulators, in addition to preventing fungal diseases. The current chapter discusses the application of beneficial and antagonistic BCAs, their effectiveness as well as bacterial-mediated mechanisms involved in the management of diseases in tomatoes. The specific mechanisms are antibiosis, competition, production of cellulolytic enzymes, cyanogenic compounds (HCN) and siderophore and induced systemic resistance (ISR). The ability of PGP rhizobacteria to antagonize a pathogen and suppress the disease through multiple pathways has been intensively studied to use them as effective BCAs. As a result, this chapter highlights a full explanation of various bacterial-mediated biocontrol mechanisms used by BCA. As environmental and health issues highlight the need to transition to a more sustainable agriculture system, the use of indigenous PGP rhizobacteria in plant disease prevention is gaining attraction. It's also recommended that using a bacterial consortium guarantees that BCA performs consistently in field settings.

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15.1 Introduction

Tomatoes (*Lycopersicum esculentum* Mill.), commonly known as 'golden apples', are the world's second most widely farmed vegetable crop after potatoes, due to their flavourful fruit and high nutritional content (Costa and Heuvelink 2018). Vitamin A, vitamin C and β-carotene, as well as vital minerals, are abundant in tomatoes (Çolak et al. 2020). It is also high in phosphorus (P), potassium (K), magnesium (Mg) and iron (Fe), all of which are needed to keep nerves and muscles functioning normally (Ali et al. 2020). Tomatoes contain β-carotene (a precursor to vitamin A) and phytosterols, making them the third-best source of vitamin C and the fourth-best source of vitamin A in human diet (Poiroux-Gonord et al. 2010). A strong antioxidant found in natural lycopene is a phyto-nutrient found in red, ripe and cooked tomatoes that helps prevent heart-related diseases and sarcoma (Kaur and Kaur 2015). Other preventive processes, such as anti-inflammatory and antithrombotic functions, are also attributed to this fruit. The short growing season, cheap cost and great economic returns have enticed growers to cultivate the crop throughout the year, even in hotter climates (Villareal 2019). Because of the diverse nature of the fruit, tomatoes are often considered a cash and industrial crop in several countries like India, the USA, China, Turkey and Egypt (Costa and Heuvelink 2018). China is the world's biggest tomato producer, with yearly production of approximately 34 million tonnes, according to international statistics (Nicola et al. 2009). Tomato output in the world is expected to be 145 million tonnes per year, covering 4.36 million ha (Chohan et al. 2017).

Tomatoes are grown all over the world due to their resilience to a wide range of soils and climates (Morganelli 2007), but their softness makes them vulnerable to insect pests and various abiotic (pesticides, heavy metals, salinity and drought) and biotic stresses (Atkinson et al. 2011). Diseases caused by phytopathogens are the primary limiting factors in overall crop losses around the world, and they are becoming increasingly important as the global population grows. Over 200 pathogen-caused illnesses have been recorded in tomatoes around the world (Watterson 1986). Seed-borne infections, on the other hand, can quickly travel from one location to another and act as the first source of inoculum (Rennie and Cokerell 2006). High-quality seeds, therefore, play an important role in producing long-term, lucrative veggies, and tomatoes are no exception to this. Microorganisms such as fungi, bacteria, viruses and nematodes cause seed-borne illnesses. Among disease-causing parasitic microbes, fungi are the most commonly seen on seeds. As a result, infected seeds have a negative impact on seed health, limiting germination capacity, poor seedling vigour, transmitting fungus pathogen to seedlings, speeding up storage deterioration, transferring pathogens into new areas and expanding the inoculum source in the field. Fungi, a crucial category of microorganisms, are responsible for a number of seed-borne illnesses of tomato, which result in significant yield losses.

Several seed-borne fungi, such as *Aspergillus flavus*, *Rhizopus solani*, *Curvularia* spp. and *Fusarium stolonifer* induce problems in tomato seeds, including wilt, necrosis, rotting and toxification of seeds (Neergard 1997). Late blight, a disease of tomato (caused by *Phytophthora infestans*), is one of the most destructive tomato diseases, resulting in significant financial losses (Fry 2020). *Sclerotinia* rot (caused by *Sclerotinia sclerotiorum*) is another major fungal infection that is threatening tomato crop productivity (Jnr 2000). Several studies have been published on *Fusarium* species-caused wilt, crown and root rot infections in tomatoes (Yezli et al. 2019). The wilt (*Fusarium oxysporum* f. sp. *lycopersici*) and early blight (*Alternaria solani*) diseases are regarded the most damaging fungal diseases that affect tomato plants.

Since the fungal diseases are pandemic, simple cultural cleanliness is ineffective. To protect the fungal diseases, chemical fungicides are often used for better yield and productivity of tomatoes. Even though agrochemicals have long been employed as a reliable method of harvest insurance, their increased use has resulted in several undesirable consequences, including disease resistance and non-target natural effects. Furthermore, the increased use of fungicides to combat tomato diseases has resulted in an increase in health risks due to phytotoxic residues and environmental consequences. As a result, it is strongly recommended that alternate disease management methods be used in place of agrochemical substances.

Managing fungal diseases using biological means is seen to be a viable method for reducing disease severity. In comparison to the previously mentioned use of chemical fungicides, the use of soil beneficial bacteria that colonize the underlying foundations of harvest plants and suppress the soil-borne illnesses is becoming an elective alternative. In this regard, PGP bacteria can be used as soil inoculants to reduce soil-borne illnesses, which is an organic solution. Because they have the potential to colonize the rhizosphere swiftly and spread down the root from a single seed treatment or soak application into the soil, PGPR with the viability of their biocontrol activity typically provide long-term protection from soil-borne diseases at the root surface. A huge number of PGPR have been recovered and characterized in the hopes of developing them as biocontrol agents for tomato illnesses. For example, Kilani-Feki et al. (2016) also employed *B. subtilis* strains to suppress the *Botrytis cinerea*, the pathogen that causes tomato fruit rot. In another study, biocontrol agents (BCAs) were recovered to combat the tomato wilt disease. It was observed that *Ochrobactrum intermedium* and *B. amyloliquefaciens*, among strains, potentially inhibited the disease incidence and increased the seedling growth and vigour indices of tomatoes (Gowtham et al. 2016). Furthermore, the effectiveness of *P. fluorescens* strains against a variety of fungal diseases (leaf blight, damping-off, stem canker, and root rot) in tomatoes (Singh et al. 2017) has been reported. Under in vitro and pothouse settings, BCAs, viz. *P. aeruginosa*, *P. fluorescens*, *B. amyloliquefaciens* and *B. subtilis* were able to successfully suppress the canker and wilt disease of tomato (Abo-Elyousr et al. 2019). Recently, a new technique for inducing systemic resistance (ISR) in plants by employing PGPR has been investigated by Attia et al. (2020). They confirmed that PGPRs were found to be effective in reducing the growth of *A. solani* (causing early blight disease) in tomato plants. In comparison to non-treated plants, they achieved an 84.3% protection rate. Effective selection, screening and safety investigation of promising PGPR strains are required for incorporating soil microbes for disease control/plant growth promotion in cropping systems and eliminating the need for chemicals. Furthermore, information on disease targeting, mass-scale production costs and procedures of registration must all be updated to improve the market standing of these BCAs. The current chapter aims to look into the potentiality of antagonistic PGP bacteria (BCAs) in managing the major fungal diseases of tomatoes. This chapter also discusses the challenges and benefits of commercializing these bacteria in the agriculture sector.

15.2 Prevalence of Seed-Borne Mycoflora: A Historical Perspective

Seed-borne fungi are microorganisms that can host the seeds both within and externally, causing diseases or contaminating the environment (Amza 2018). Phytopathogenic fungi may cause post-germination death, rendering them poisonous and lowering their quality for human food and seed production. The conidia, oospores, sclerotia, hyphae and chlamydospores are some examples of the main forms in which they are present (Arora 1986). The tomato, which is employed as a model crop in genetics, is susceptible to a variety of seed-borne fungal diseases.

A total of 12 phytopathogenic fungi were recovered from the fruits and seeds of *Solanum lycopersicum*. It was found that the majority of the pathogens were habitants of fruits; however, the species of *Cladosporium* were detected in seeds (Dhekle and Bodke 2013). In reality, a considerable number of fungal isolates belonging to genera *Fusarium*, *Pythium, Botrytis*, *Alternaria* and *Rhizoctonia* were found in tomato seeds, causing several seeds-borne diseases. Mycoflora are isolated as surface contaminants, internally seed-borne flora, and are known to cause major field diseases depending on the presence of fungi on the seed coat or in the seed. Various fungal phytopathogens, viz. *F. oxysporum*, *Alternaria solani*, *Aspergillus flavus*, *A. fumigatus*, etc., have been detected and identified from infected tomato plants and reported to cause serious seed damage (Fig. 15.1) as reported by several workers. The investigation of grey mould disease in tomato leaves was done using a hyperspectral imaging technique based on competitive adaptive reweighted sampling (CARS) and correlation analysis (WANG et al. 2017). Similarly, tomato plants were infected by fungal pathogens like *F. semitectum* (1–3% infection), *F. moniliforme* (0.5% infection), and *Curvularia lunata* (0.5–7.5% infection) and *Bipolaris* spp. (1.5% infection) (Bhatti et al. 2010). The duration of storage has a significant impact on the prevalence of various mycoflora. On a modest scale, *Phytophthora infestans* has caused the full destruction of tomato harvests around the world (Panthee and Chen 2010). *Hormonema* spp., one of the most prevalent genera on tomato seeds, were discovered by Nishikawa et al. (2006) while assessing 109 species of seed-borne fungi from three cultivars of tomato. The seed could be

Fig. 15.1 Major tomato diseases caused by fungal pathogens. Early blight (*Alternaria solani*) (**a**), late blight (*Phytophthora infestans*) (**b**), buckeye rot (*Phytophthora*) (**c**), septoria leaf spot (*Septoria lycopersici*) (**d**), anthracnose (*Colletotrichum*) (**e**), verticillium wilt (*Verticillium dahliae*) (**f**), southern blight (*Sclerotium rolfsii*) (**g**), fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*) (**h**) and grey mould (*Botrytis cinerea*) (**i**) (source: https://www.google.com/)

diseased within or be contaminated on the exterior. The fungus *F. oxysporum* f. sp. *lycopersici* causes fusarium wilts, one of the most destructive diseases of tomatoes. Similarly, previous researchers found a total of 17 fungal phytopathogens linked with tomato var. local seeds, with *Aspergillus niger*, *A. flavus*, *Fusarium moniliform*, *Rhizopus nigricans*, *Curvularia lunata* and *Alternaria alternata* being the most prevalent. In the Indian state of Gujarat, 12 fungi were discovered with four tomato cultivar seeds. *A. alternata*, *A. flavus* and *A. niger* were the most common, whereas *A. amstelodami* and *Cunninghamella echinulata* were discoveries.

15.3 Management of Fungal Diseases in Tomatoes

In the fight against crop diseases, seed health is crucial. The rise of endemic diseases as a result of changing global environment poses a difficulty in maintaining the health of the plant. As a result, timely and precise diagnosis of the problem, as well as pathogen surveillance, gives time for mitigation actions to be implemented. Treatment of seeds to destroy pathogens carried within or on the seed has been demonstrated to be effective in preventing epiphytotic plant diseases. Seed-borne fungi, on the other hand, are easy to control compared to airborne or soil-borne fungi. Farmers are encountering financial difficulties as a result of significant crop losses caused by seed-borne mycoflora on their crops. Controlling seed-borne infections via various approaches is a crucial element in every agricultural crop production and protection programme. To eliminate pathogens from seeds both inside and externally, as well as to protect seeds from soil-borne diseases, a variety of chemical, biological, physical, and mechanical techniques have been applied (Shahid et al. 2017).

15.3.1 Use of Chemical Fungicides (Chemical Method)

Mycotoxins released by seed-borne fungal pathogens cause serious issues in humans. Hence, seeds should be treated with appropriate chemical before planting. Chemical fungicides are used since pre-historic times for the management of phytopathogenic fungi and for obtaining a better yield of crops. Historically, treating seeds with chemical fungicide using spraying, drenching of soils and dusting has been important (Copping and Duke 2007). These methods could protect the seeds and seedlings from the soil-dwelling fungal pathogens causing damping-off and rot diseases (Divya Rani and Sudini 2013). Amini and Sidovich (2010) conducted in vitro and in vivo experiments where they used six chemical fungicides, viz. fludioxonil (FLN), bromuconazole (BMZL), benomyl (BML), carbendazim (CBZM), azoxystrobin (AZBN) and prochloraz (PCZ), against the fusarium wilt disease in tomato crop. When administered to seedlings at prescribed levels, PCZ and BMZL were found to be the most effective against *Fusarium oxysporum* f. sp. *lycopersici*. Among the fungicides tested, FLN and BMZL showed a phytotoxic impact on tomato seedlings. Similarly, in another investigation, Al-Kassim and Monawar (2000) treated (in vitro) five vegetable seeds including *Solanum lycopersicum*, *Solanum melongena*, *Abelmoschus esculentus*, etc., in Gazan province with 0.2% of chemical fungicides like benomyl, cozib and mancozeb before incubation. The majority of the isolated fungi were inhibited by all of the tested fungicides. Benomyl, on the other hand, was the most effective against all of the fungi found on the seeds of the tomato.

Major fungal diseases of tomatoes, their symptoms and chemical control measures

S. no.	Disease	Causal agent	Symptoms	Chemicals used	Effectiveness	Reference
1	Early blight	*Alternaria solani*	• Brown-black spots (in the form of lesion 1/2-inch diameter) • Formation of blotches (irregular) • Defoliation, browning of infected leaves • Appearance of lesion (dark) on stems • Girdling of the stem or collar rot	Mancozeb 80WP, Bavistin 50WP, Indofil M-45, Sulcox 50WP and Tall-25EC, chlorothalonil (0.2%), kasugamycin (0.2%), azoxystrobin (0.1%), propiconazole (0.1%), pyraclostrobin (0.2%), perfekt (0.2%), metalaxyl (0.2%), mancozeb (0.25%)	Suppressed the fungal growth Reduced the disease incidence	Roy et al. (2019), Arunakumara et al. (2010)

(continued)

S. no.	Disease	Causal agent	Symptoms	Chemicals used	Effectiveness	Reference	209
2	Septoria leaf spot	*Septoria lycopersici*	• Disease infection on lower leaf • Symptoms also occur on stems and blossom • Symptoms on fruits appear in the form of small-sized water-soaked spots • Development of greyish white centres with dark edges • Yellowing, withering of leaves and ultimately fall off	Fungicides pyraclostrobin (116.6 ppm), fluxapyroxad (58.5 ppm), mancozeb (4000 ppm), difenoconazole (125 ppm), chlorothalonil (1500 ppm), propineb (2100 ppm), fluazinam + thiophanate-methyl (375 + 375 ppm) and metiram + pyraclostrobin (1100 + 100 ppm)	Suppressed the fungal growth Reduced the disease incidence	Monteiro et al. (2021)	210
3	Late blight	*Phytophthora infestans*	• Younger/older leaves infected • Appearance of pale-green water-soaked spots starting at leaf tips that enlarge rapidly, forming irregular, greenish-black blotches • Development of white moulds at the margins of infected areas • Under the favourable condition, whole plants rapidly defoliated • Infection on petioles and stems occurs as brown streaks	Fungicides oxathiapiprolin, chlorothalonil, azoxystrobin, mandipropamid and mefenoxam were effective against the disease	Chemicals single or in mixture controlled the disease Suppressed the growth of pathogens Improved the growth and yield of tomato	Cohen et al. (2018)	211
4	Fusarium wilt	*Fusarium oxysporum* f. sp. *lycopersici*	• Development of leaves • Affected leaves soon wilt and dry up, but they remain attached to the plant • The wilting continues successively on younger foliage and eventually results in plant death • The stem remains firm and green on the outside but exhibits a narrow band of brown discolouration in the vascular tissue • Brown streaking in the vascular tissue of infected plants becomes plugged during the attack by the fungus, leading to wilting and yellowing of the leaves	Chemical fungicides difenoconazole (200 mg/L), benomyl, carbendazim, prochloraz, fludioxonil, bromuconazole and azoxystrobin were effective		Amini and Sidovich (2010)	212
5	Verticillium wilt	*Verticillium dahliae*	• Leaf edges and areas between the veins turn yellow and then brown • Infected plants often have a characteristic V-shaped lesion at the edge of the leaf	Nano-fungicide (leaf extract olive oil-loaded chitosan nanoparticles)	Diminished the disease symptoms	Mazzotta et al. (2022)	213

(continued)

	S. no.	Disease	Causal agent	Symptoms	Chemicals used	Effectiveness	Reference
214				occurring in a fan pattern • As the disease progresses, younger leaves begin to wilt and die, until only a few healthy leaves remain at the top of the plant			
214	6	Anthracnose	*Colletotrichum*	• Symptoms appear first as small, circular, slightly sunken lesions on surface of ripening fruits • Spots quickly enlarge, become bruise like depressions and develop a water-soaked appearance directly beneath the skin (epidermis) of the fruit • As these spots expand, they develop dark centres or concentric rings of dark specks the rings consist of numerous small spore-producing bodies	Azoxystrobin-based fungicides Onestar 23% SC and Amistar 23% SC	Decreased the incidence of disease (69–71%)	Saxena et al. (2016)
215	7	Buckeye rot	*Phytophthora*	• Symptoms appear as water-soaked greyish-green/brown spots • Further, spot enlarges and develops into a lesion with a target-like pattern of concentric rings of narrow dark-brown and wide light-brown bands	Application of fungicides metalaxyl, cymoxanil, mancozeb and copper oxychloride	Reduced the incidence of disease	Gupta and Bharat (2008)
216	8	Southern blight	*Sclerotium rolfsii*	• Formation of wilting on plants • Development of water-soaked lesion on stems • Produced sclerotia are white, later becomes dark-brown (spherically structured) • White mycelium and sclerotia at stem base of infected plants are the main symptoms of disease	Fungicides pyraclostrobin, quintozene and fluxapyroxad were used	Chemicals significantly reduced the disease incidence	Keinath and DuBose (2017)
217	9	Grey mould	*Botrytis cinerea*	• Appearance of grey-brown velvety mould covering on stems/ younger leaves • Grey spores cover dying flowers and the calyx of fruit	Difen Super, 55% WP fungicide concentration of 0.08% with active ingredient, difenoconazole, and fungicide Skor, 250 g/l EC with concentration of 0.05% and 0.07%	Effective against the pathogen	Zuparov et al. (2020)

15.3.2 Biological Management

Chemical fungicides have a significant impact on seed-borne fungal infections, but they also have a negative impact on beneficial microbial diversity in soils as well as crop productivity. Furthermore, irregular fungicidal usage is not only harmful to animals and humans but also leads to development of resistance among the pathogens targeted. Because fungicides are harmful to non-target organisms (Marinho et al. 2020), scientists are turning to more environmentally benign and cost-effective means of disease management, such as acid treatments, and the use of antagonistic microbes (Droby et al. 2022), and plant extracts (Shuping and Eloff 2017). These are interesting and viable options for releasing plant growth regulators that influence overall crop development and improve morpho-physiological features. The method of biocontrol has been utilized for over 2000 years, and it has been widely used in managing pests since the end of the eighteenth century. The types of biological control can be classified into natural, conservation, inoculative (classical) and augmentative biocontrol. Natural biocontrol has been used to reduce pests since evolution, whereas conservation biocontrol comprises human measures to stimulate and protect the performance of natural foes. The inoculative mode of biocontrol is the most extensively used type of biocontrol, in which natural enemies are dispersed into new places where the pest has been mistakenly introduced. Natural enemies are mass-produced in bio-factories and sent into the market for fast pest control, making augmented biocontrol more appealing. This type of plant protection is regarded to be both environmentally beneficial and food-safe. Moreover, gaining a better knowledge of biocontrol mechanisms via interactions between BCAs and phytopathogens may aid in the improvement and development of biocontrol systems.

15.4 Plant Growth-Promoting Rhizobacteria: Tapping for BCA

Rhizobacteria are a varied collection of bacteria that colonize the rhizosphere environment. In the root zone, they are strong microbial competitors. They either directly or indirectly influence plant development. The direct method entails PGPR's positive effects that directly boost plant growth. These systems help plants grow, but the ways they do so differ from species to species and strain to strain (Noori and Saud 2012). Through biogeochemical cycling, the PGPR nourishes the plant by converting the nutrients into the soil. They also help plant growth by facilitating the transfer of these nutrients into the plant. They promote plant growth by synthesizing plant hormones such as indole acetic acid (Ahmed et al. 2021), cytokinins (Liu et al. 2013), fixing nitrogen from the atmosphere (Malik et al. 1997), solubilizing minerals like phosphorus (Gomez-Ramirez and Uribe-Velez 2021) and generating siderophores that can solubilize and sequester iron (Sultana et al. 2021) and provide nutrients to plants (Etesami and Adl 2020) in addition to combating soil-borne plant diseases (Hamid et al. 2021). It plays a significant effect in repelling phytopathogenic bacteria in addition to promoting plant growth (Hassan et al. 2019). *Bacillus subtilis* has a biocontrol efficiency of more than 50% on tomato plants against the plant disease caused by *Ralstonia solanacearum* in greenhouse conditions (Chen et al. 2013). *Rhizoctonia solani*, which causes damping-off in tomatoes, was controlled by a strong biocontrol agent, *Priestia endophytica* FH5 (Zhou et al. 2021). The biofortified vermicompost prepared from chosen BCAs (like *B. subtilis* and *P. fluorescens*) could be used to successfully manage the wilt diseases in tomatoes caused by *Fusarium oxysporum* (Basco et al. 2017). In a similar study, *S. pratensis* strain LMM15 (having the potential of BCA) was sprayed on tomato leaves 1 day before fungal inoculation. After BCA spraying, it was observed that the occurrence of grey mould disease was reduced by approximately 46%. Furthermore, the applied biocontrol agent significantly increased the plant stressor metabolites (proline and lipid peroxidation) as well as defence enzymes in shoot tissues (Lian et al. 2017). These strains of actinomycetes drastically reduced the pathogen proliferation while also improving tomato growth characteristics (Goudjal et al. 2014).

15.5 Mechanisms Involved in Disease Suppression (Indirect Mechanisms)

The PGPR's antagonistic characteristics against a variety of diseases expand their potential as biocontrol agents (Fatima et al. 2022). Several genera of beneficial soil bacterial strains including *Pseudomonas* (Kabdwal et al. 2019), *Bacillus* (Ni and Punja 2019), *Enterobacter* (Xue et al. 2009), *Serratia* (Youssef et al. 2016), *Klebsiella* (Gaur et al. 2017), *Azotobacter* (Alsudani 2022), etc. are familiar as biological control agents (BCAs) used in reducing tomato diseases. Many reports claim that using the PGP consortium as biological control agents has some advantages over other disease control methods, such as being an environmentally safe and non-toxic indigenous microorganism whose application is both environmentally safe and favourable to human health. Induction of systemic resistance (ISR), antibiotic production, competition, secretion of cellulolytic/hydrolytic enzyme and production of HCN and siderophores are all essential mechanisms involved in BCA's antagonistic effects (Narayanasamy 2013). Furthermore, they can help plants cope with numerous stressors such as salinity, drought, hunger, heavy metal toxicity and so on, allowing them to thrive in such environments. Even though various free-living PGPR are regarded as plant development beneficial microbes, not all the strains within the same species have the same metabolic capacity to boost plant growth. It's crucial to understand the rhizosphere microbiota's capabilities, as well as its mechanisms of action, to ensure long-term crop production (Babalola et al. 2021). The PGPR's antagonistic characteristics against a variety of diseases expand their potential as BCAs (Verma et al. 2019). Various genera of *Bacillus* including *Bacillus megaterium, B. subtilis* and *B. polymyxa*, *P. fluorescens* and *T. harzianum* were co-inoculated with *Azospirillum* sp. and *Azotobacter* sp. and were reported to effectively control the disease caused by fungal pathogens (Saad et al. 2016).

Some biocontrol agents (BCAs) involved in the management of major fungal diseases of tomatoes

S. no.	Major fungal disease	Causal agent	Biocontrol agent involved	Mechanism involved	Effectiveness	Reference	299
1	Fusarium wilt disease	*Fusarium oxysporum* f. sp. *lycopersici*	*Bacillus* sp.	Production of cell wall-degrading enzymes like β-1,3-glucanase, protease, chitinase, ammonia, siderophore, HCN production, bioactive volatile and non-volatile metabolites	• Reduced the disease severity up to 55%. Enhanced the growth and physiological traits of plants	Jangir et al. (2018)	300
2	Tomato vascular wilt	*Fusarium oxysporum*	*Bacillus velezensis* NKG-2	Volatile organic compounds (VOCs)	• Suppressed the disease severity • Increased the growth of plants	Myo et al. (2019)	301
3	*Botrytis cinerea*	Grey mould disease	*Bacillus subtilis* L1–21	Antifungal metabolites	• Completely inhibited (100%) the fungal growth • Increased the plant growth and improved the fruit quality	Bu et al. (2021)	302
4	Alternaria rot disease	*Alternaria alternata*	*Bacillus atrophaeus*	Antifungal metabolites O-anisaldehyde And lipopeptides	• Reduced the germination of the spore. • Decreased the disease severity of *Alternaria* in tomato fruit.	Chacon-Lopez et al. (2021)	303
5	Black scurf disease	*Rhizoctonia solani*	*Bacillus subtilis Hussain T-AMU*	Lipopeptide, biosurfactant	• Inhibited the growth of the pathogen • Inhibited the incidence and severity of disease	Hussain et al. (2021)	304
6	Alternaria leaf blight	*Alternaria solani*	*Bacillus velezensis* NKMV-3	Production of lipopeptide (antibiotic synthesis genes), *iturin C*, *surfactin A* and *fengycin B* and *D*	• Controlled the growth of the pathogen	Vignesh et al. (2022)	305
7	Fusarium wilt disease	*Fusarium oxysporum* sp. *lycopersici*	*Bacillus inaquosorum* KR2-7	Production of BGCs fengycin, surfactin and bacillomycin F, bacillaene, macrolactin, skf, subtilosin A, bacilysin and bacillibactin	• Reduced the disease severity • Increased defence-related enzyme activities	Kamali et al. (2022)	306
8	Early blight disease	*Alternaria alternata*	*Bacillus* sp.	Antibiosis, production of volatile organic compounds	• Decreased the disease severity	Pane and Zaccardelli (2015)	307

(continued)

	S. no.	Major fungal disease	Causal agent	Biocontrol agent involved	Mechanism involved	Effectiveness	Reference
308		Wilt disease	*Verticillium dahliae*	*Bacillus subtilis*	Various antibiotic metabolites and VOCs	• Suppressed the fungal infection, increased tomato yield	Rahman et al. (2021)
309	9	Foliar blight disease	*Botrytis cinerea*	*B. nakamurai, B. pseudomycoides, B. proteolyticus, B. thuringiensis, E. asburiae* and *E. cloacae*	Antifungal VOCs such as 3-methylbutan-1-ol, sulphur-containing compounds, 2-heptanone and dodecanal	• Increased the growth and yield of tomato	Chaouachi et al. (2021)
310	10	Anthracnose disease	*Colletotrichum capsici*	*Bacillus* sp. *strain M10*	Extracellular enzyme production	• Suppressed the fungal growth	Srikhong et al. (2018)
311	11	Fusarium wilt	*Fusarium oxysporum* f. sp. *lycopersici*	*Bacillus pumilus*	Loss of protoplasm in fungal cell wall	• Reduced (73%) disease incidence • Increased root (60%) and shoot (84%) of tomato	Heidarzadeh and Baghaee-Ravari (2015)
312	12	Early blight and anthracnose disease	*Alternaria solani*, *Colletotrichum coccodes*	*Pseudomonas fluorescens A506*	Antifungal antibiotics and VOCs	• Suppressed anthracnose on fruit and early blight on detached leaves, controlled the disease in tomato	Cuppels et al. (2013)
313	13	Early blight disease	*Alternaria solani*	*Pseudomonas fluorescens*	Antifungal antibiotics and VOCs	• Inhibited (45.55%) the fungal growth	Koley et al. (2015)
314	14	Grey mould disease	*Botrytis cinerea*	*Bacillus licheniformis*	Antifungal compounds	• Inhibited the fungal growth • Controlled the disease incidence (90%) in tomato	Lee et al. (2006)
315	15	Foot rot disease	*Fusarium oxysporum* f. sp. *radicis-lycopersici*	*Collimonas fungivorans*	Antifungal compounds, cell wall-degrading enzymes	• Suppressed the fungal growth	Kamilova et al. (2007)
316	16	Black scurf and wilt disease	*Rhizoctonia solani, fusarium oxysporum*	*Bacillus subtilis* (TD11), *Bacillus cereus* (TD15)	Secretion of antifungal metabolites Induced systemic resistance (ISR)	• Inhibited the growth of *Rhizoctonia solani* (40%) and *Fusarium oxysporum* (80%) • Controlled (50%) the disease incidence in tomato	Malik et al. (2022)
317	17	Root rot disease	*Sclerotium rolfsii*	*Bacillus* sp.	Production of hydrogen cyanide (HCN) and extracellular enzymes	• Suppressed the fungal growth • Reduced the disease incidence	Kumar et al. (2012)

(continued)

S. no.	Major fungal disease	Causal agent	Biocontrol agent involved	Mechanism involved	Effectiveness	Reference	
							318
18	Fusarium wilt disease	*Fusarium oxysporum*	*Pseudomonas* sp.	Siderophore production	• Suppressed the fungal growth Reduced the disease incidence	Arya et al. (2018)	319
19	Fusarium wilt disease	*Fusarium oxysporum*	*Streptomyces* SNL2	Synthesis of phenolate siderophore	• Reduced the prevalence of wilt disease by 88.5%	Goudjal et al. (2016)	320
20	Early blight of tomato	*Alternaria solani*	*Lysinibacillus fusiformis* L-2, *Bacillus subtilis* B-1 and *Achromobacter xylosoxidans* A-3	Production of siderophore and other antifungal compounds	• Suppressed the fungal growth • Controlled the disease • Improved the growth features of tomato crop	Attia et al. (2020)	321
21	Fusarium wilt disease	*Fusarium oxysporum*	*B. pumilus*	Siderophore production	• Suppressed the fungal growth. Reduced the disease incidence	Heidarzadeh and Baghaee-Ravari (2015)	322
22	Fusarium wilt	*F. oxysporum* f. sp. *lycopersici*	*Burkholderia contaminans* AY001	Systemic induced resistance (ISR), production of antimicrobial compounds, including di (2-ethylhexyl) phthalate and pyrrolo [1,2-a] pyrazine-1,4-dione, hexahydro-3-(phenylmethyl)	• Enhanced the growth of tomato plants • Increase the disease resistance • Improved the yield attributes	Heo et al. (2022)	323
23	Fusarium wilt	*Fusarium oxysporum*	*Pseudomonas aeruginosa*	Production of antifungal metabolites like siderophore, HCN and ammonia	• Inhibited the fugal growth (75%) • Increased the growth parameters	Parasuraman et al. (2022)	324
24	Early blight	*Alternaria solani*	*Pseudomonas aeruginosa*	Production of antifungal metabolites like siderophore, HCN and ammonia	• Inhibited the fugal growth (75%) Increased the growth parameters	Parasuraman et al. (2022)	325
25	Early blight disease	*Alternaria alternata*	*B. atrophaeus and Brevibacterium frigoritolerans*	Induced systemic resistance (ISR) Secretion of extracellular enzymes	• Suppressed the fungal growth • Reduced the disease incidence • Increased the plant growth and biomass	Chacon-Lopez et al. (2021)	326
26	Verticillium wilt disease	*Verticillium dahliae*	Pseudomonas stutzeri	Synthesize antifungal metabolites like HCN, siderophore and other extracellular enzymes	• Enhanced the growth characteristics (stem length, number of leaflets, leaf area and root	Essalimi et al. (2022)	327

(continued)

S. no.	Major fungal disease	Causal agent	Biocontrol agent involved	Mechanism involved	Effectiveness	Reference
					weight) and biochemical parameters (nitrate reductase activity, proline and chlorophyll content) of tomato.	
27	Fusarium wilt disease	*Fusarium oxysporum* f. sp. *lycopersici*	*Pseudomonas fluorescens* Pf1	Secretion of essential plant growth-regulating substances, synthesize antifungal metabolites	• Decreased the disease incidence • Improved the germination, vigour indices, growth and biomass of tomato	Johnson et al. (2022)
28	Collar rot disease	*Sclerotium rolfsii*	*Pseudomonas fluorescens* Pf1	Synthesize antifungal compounds	• Suppressed the growth of pathogen • Reduced the disease incidence	Johnson et al. (2022)

15.5.1 Production of Antibiotics

The chemical compounds which are produced by a species of microbes and are used to kill other species of microbes are known as antibiotics. To survive predation, competition and other threats, microorganisms interact with each other and produce these chemical molecules (Kaya and Koppenhöfer 1996). Bacterial antagonists decrease phytopathogens by secreting inhibitory compounds into the extracellular environment (Freitas et al. 2022). It is a highly effective and extensively researched aspect of biocontrol. The 2,4-diacetylphloroglucinol (DAPG), pyrrolnitrin, phenazine, tensin, pyoluteorin, tropolone, oomycin A, cyclic lipopeptides and hydrogen cyanide (HCN) are some of the well-known antibiotics for biological control (Saeed et al. 2021). The majority of antibiotics produced by *Bacillus* sp. are effective against plant harmful fungi *Fusarium oxysporum* and *Alternaria solani* (Zhang et al. 2020). *B. subtilis* has been reported as a strong biocontrol agent, and it inhibited the fungal growth by producing a wide range of antibiotics, including bacilysin, bacillomycin, fengycin, zwittermicin and difficidin (Kim et al. 2010; Telang 2010). *Bacillus* strain TNAM5 was discovered to be effective in suppressing FOL by producing diffusible and volatile organic (VO) antifungal compounds, ammonia and HCN (Prashar et al. 2013; Kumari et al. 2021). Phichai (2014) discovered that *B. subtilis* could generate antifungal metabolites (bacitracin, subtilin, bacillin and bacillomycin) that inhibited *Alternaria* spp. However, because antibiotic resistance is a problem, having too much reliance on antibiotic-producing bacteria as a BCA could be a disadvantage.

15.5.2 Competition

Effective colonization and increased competition are important factors in biocontrol; thus, the biological control agents (BCAs) should be able to tolerate and multiply in a natural environment (Pal and Gardener 2006). Microorganisms must efficiently compete for accessibility of nutrition and niche to establish themselves in the rhizosphere (Lugtenberg 2015). Biocontrol mainly relies heavily on competition between pathogenic and non-pathogenic microorganisms (Daguerre et al. 2014). Plant-associated bacteria are known to provide more protection to the plant by accelerating rhizosphere penetration than pathogens. Biocontrol chemicals exhaust the few available substrates, rendering them inaccessible to infections. At the same time, they produce metabolic chemicals that are harmful to infections (TariqJaveed et al. 2021). As a result, an effective BCA must be able to safeguard the deeper root sections by colonizing well and suppressing the pathogen at the growing tips. In rhizobacterial populations, species of *Pseudomonads* have been identified as very efficient competitors for root exudates (Kuiper et al. 2002). Antimicrobial chemicals are found in some root exudates, providing a favourable ecological niche for PGPR, which may then detoxify them (Badri and Vivanco 2009). This means that PGPR competence is heavily contingent on their capacity to exploit specific environmental conditions or adapt to changing conditions (Amaya-Gómez et al. 2020). Kuiper et al. (2001) found that root colonizing *Pseudomonads*' competitive colonization ability was strongly influenced by their enhanced intake of putrescine, a tomato root exudate.

15.5.3 Induced Systemic Resistance (ISR)

Beneficial bacteria living in the rhizosphere region interact with the host plant to help it fight against different phytopathogens (Kumar and Jagadeesh 2016). The enhanced physiological state of defence elicited by broad-spectrum biotic and abiotic stimuli is known as induced resistance. The induction of systemic resistance is characterized by (1) induced systemic resistance (ISR) and (2) systemic acquired resistance (SAR). ISR occurs when plants' intrinsic defence mechanisms are triggered in response to biotic threats (Pineda et al. 2013). Plants in SAR develop greater resistance to uninfected plant sections while dealing with a wide range of diseases (Pieterse et al. 2001). ISR is primarily mediated by the jasmonate or ethylene-sensitive pathway, whereas SAR is mediated by salicylic acid (SA) (Mandal and Ray 2011). Rhizobacteria invading plant roots can induce resistance to a wide range of illnesses. It has been reported that some strains of *Bacillus* (Choudhary and Johri 2009), *Pseudomonas* (Jisha et al. 2019), *Burkholderia* (Ahmad et al. 2022) and *Serratia* (Singh and Jha 2016) cause ISR in response to various infections. By evoking such induced resistance, BCAs display the inhibition of diseases caused by fungal, bacterial, viral and, in some cases, insects and nematodes. The genus

Bacillus is an excellent BCA and the most widely used biopesticide for controlling plant diseases (Miljaković et al. 2020). Some species of *Pseudomonas* also play an imperative role in ISR. For example, *P. fluorescens* was found to provide ISR to tomato plants against the diseases causing fungal pathogens (such as *P. infestans* and *F. oxysporum*) (Santoyo et al. 2012). The use of potential *Pseudomonas fluorescens* VSMKU3054, an efficient BCA, gave clear evidence of ISR-mediated biocontrol of tomato grey mould disease (Suresh et al. 2022). In a study, Chunyu et al. (2017) evaluated the efficiency of PGPR strain *B. amyloliquefaciens* SQRT3 to prevent the tomato crop against pathogens by inducing a systemic resistance mechanism. In a crop-based study, it was observed that by activating the various defence enzymes (PPO, POX, GLU, CHI and PAL), and induction of systemic resistance, antagonistic PGPR strains *S. marcescens*, *Streptomyces cereus* and *Bacillus cereus* increased the resistance of wilt disease in tomato (Ferraz et al. 2015). Reduction in the severity of disease and enhanced upregulation of defensive enzymes triggered by the combined inoculation of *Bacillus atrophaeus*, *B. subtilis*, and *Burkholderia cepacia* exhibited a direct biocontrol and ISR mode of action for suppression of vascular disease in tomato crops (Shanmugam and Kanoujia 2011). Similarly, by activating and upsurging the activities of peroxidase, PPO and phenylalanine ammonia-lyase, the biocontrol agent *Pseudomonas putida* stimulated the systemic responses in tomatoes against early blight disease (Ahmed et al. 2011). In another study, antagonistic bacteria *B. subtilis* OTPB1 suppressed the early blight of tomato (caused by *A. solani*) due to increased systemic response. The bacterial-inoculated tomato seedlings had significantly higher levels of defence-related enzymes (peroxidase, PO; polyphenol oxidase, PPO; and superoxide dismutase, SOD) than uninoculated control seedlings (Chowdappa et al. 2013). In the external environment, bacteria produced exopolysaccharides (EPS). The EPS aids in drought resistance, stress resistance and phytopathogen defence (Fig. 15.2). In various crops, the significant function of bacterial EPS as an elicitor for the generation of systemic resistance has already been established. The exopolysaccharide synthesized by *Bacillus* sp. EPS has been shown to effectively minimize the occurrence of wilt disease in tomatoes caused by *F. oxysporum* (Thenmozhi and Dinakar 2014).

15.5.4 Production of Cellulolytic/Cell Wall-Degrading Enzymes

Cellulolytic/cell wall-degrading enzymes secreted and excreted by certain bacteria can disrupt pathogen development and/or activity. The secretion of these enzymes is a cost-effective way to stop pathogen proliferation through the lysis of pathogenic cell walls. Several bacterial genera produce and release lytic enzymes that are capable of hydrolyzing a wide range of polymeric materials (proteins chitin, cellulose, hemicellulose and DNA). This technique allows the phytopathogen to be directly parasitized. The release and expression of these enzymes by various

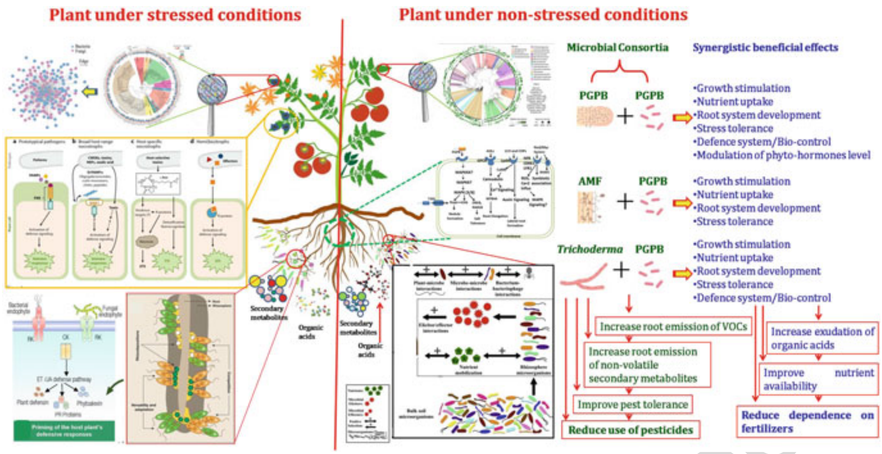

Fig. 15.2 An overview of microbe-mediated modulation of physio-biochemical and molecular mechanisms of biotic stress tolerance in plants. Photograph clearly depicts that plant secreted chemically different biochemicals/secondary metabolites which regulate recruitment of microbial strains under stressed and non-stressed conditions. These microorganisms further regulate the defence mechanisms in plants. Figure showed the multi-trophic interactions in the rhizosphere which define the active rhizosphere effects and how the microbiome served as the first line of defence and maintain defence level and plant growth under stressed conditions

microorganisms can occasionally directly decrease plant pathogen activity. Polymeric components (such as cellulose, hemicelluloses, chitin, proteins and DNA) found in fungal cell walls can be digested by lytic enzymes including cellulase, chitinase and protease, among others. *Pseudomonas* sp., among soil bacteria, has gotten increased attention since it can produce a variety of cell wall disintegrating enzymes, including chitinase, protease/elastase and 1,3-glucanase (Wang et al. 2021).

Chitinases and 1,3-glucanases are two of the most important hydrolytic enzymes involved in the breakdown of fungal cell walls. Mycolytic enzymes produced by rhizobia, particularly chitinases, are known to hydrolyze chitin, a significant component of fungal cell walls (Chavan and Deshpande 2013). Production of extracellular cellulolytic enzymes (cellulase, chitinases, protease and β-1,3-glucanase) by *Bacillus* sp. recovered from *Solanum lycopersicum* rhizosphere inhibited the fungal pathogens and proved to be a viable bioresource for the agricultural business (Kumar et al. 2012). In a study, Ramyabharathi and Raguchander (2014) found that antagonistic PGPR strain *B. subtilis* EPCO16 produced HCN and volatile organic compounds (VOCs) together with proteolytic and extracellular enzymes chitinase and β-1,3-glucanase. This strain retarded the growth of *F. oxysporum* f. sp. *lycopersici* causing fusarium wilt disease in tomatoes and proved to be a successful biocontrol agent in managing the fungal diseases. Further, strains of *Pseudomonas* (*P. fluorescences* NRC1 and *P. fluorescens* NRC3) inhibited the phytopathogens

Phytophthora capsica and *R. solani* (the causal agents of root rot disease in tomato) by secreting different cell wall-degrading enzymes and synthesizing antifungal metabolites (Moataza 2006). Under greenhouse circumstances, the strain *Bacillus* sp., which could synthesize different types of extracellular enzymes, reduced the disease incidence of wilt disease (caused by *F. oxysporum* f. sp. *lycopersici*) by 36% in tomato plants, suggesting that it could be an effective biocontrol agent for tomato wilt (Jangir et al. 2018). *P. fluorescens* has also been identified as a potent BCA against the fungal pathogen, stimulating important enzymes such as peroxidase (POX), polyphenol oxidase (PPO) and superoxide dismutase (SOD), as well as 1,3-glucanases (Dorjey et al. 2017). Apart from the extracellular enzymes, the inhibition of phytopathogens could also be aided by other microbial by-products. For instance, at picomolar concentrations, hydrogen cyanide (HCN) efficiently disables the cytochrome oxidase pathway and is extremely hazardous to all aerobic microbes. Hydrolytic enzymes produced by some identified strains of *Bacillus* have been described for the biocontrol of the phytopathogen *F. oxysporum* causing wilt disease in tomatoes (Jadhav and Sayyed 2016). The efficiency of different rhizobacterial strains is dependent on the host plant and soil factors, in addition to the biocontrol methods listed above. Furthermore, their innate capacities and rhizosphere competence play a significant role in the manifestation of their biocontrol features (Weert and Bloemberg 2007). In a field trial, Shanmugam and Kanoujia (2011) evaluated the biocontrol potential of antagonistic PGPR strains, *B. cepacia* and *B. subtilis* against *Fusarium oxysporum* f. sp. *lycopersici* causing wilt disease in tomato. They found that the bacterial strains reduced the incidence of disease by secreting extracellular enzymes. Further, they claimed that leaf and root sample analyses had the highest induction of chitinase and 1,3-glucanase.

15.5.5 Production of Hydrogen Cyanide (HCN)

Hydrogen cyanide (HCN) is an antibacterial and antifungal molecule well known for its ability to prevent disease (Haas and Keel 2003). HCN is likely to disrupt the electron transport chain (ETS) and the cell's energy source, resulting in cell death. Cytochrome oxidase is also known to be inhibited by the action of HCN (Cooper and Brown 2008). This detrimental characteristic gives PGPR a competitive advantage over fungal pathogens, and it can be used in plant disease biocontrol (Shaikh and Sayyed 2015). Among rhizosphere microbes, *Pseudomonas* and *Bacillus* spp., for example, produce cyanogenic compound (HCN) as a secondary metabolite (Sivasakthi et al. 2014). Bacterial cyanogenesis has also been described in the species of *Burkholderia* (Shahid and Khan 2018), *Achromobacter* (Oves et al. 2019), *Bacillus* (Hassan et al. 2010), and *Azotobacter* (Shahid et al. 2019). However, fluorescent *Pseudomonas* is the most common HCN produce (Keerthana et al. 2022). The majority of research suggests that HCN-producing bacteria are active against fungal infections and, thus, serve as a biocontrol agent (Sehrawat et al. 2022; Haddoudi et al. 2021; Hernández-León et al. 2015; Pandya and Saraf 2014). In a study, Kumar et al. (2012) found that HCN-synthesizing *Bacillus* sp. suppressed the disease-causing pathogen *Sclerotium rolfsii*. Similarly, PGPR strain *Beijerinckia fluminensis* suppressed the growth of major fungal phytopathogens while assessed under in vitro conditions (Al-Shwaiman et al. 2022).

15.5.6 Production of Siderophore

Iron (Fe) is a necessary micronutrient for all living things and is found in the soil mostly in the form of ferric ion (Fe3+), which is only sparingly soluble. As a result, plants are unable to absorb it. Plants can utilize the microorganism-produced siderophores to absorb iron (Radzki et al. 2013). Beneficial soil microbial diversity synthesizes siderophores (low-molecular-weight Fe-chelating molecules) having high affinity and selectivity for binding and forming a complex Fe complex (III) (Colombo et al. 2014). It functions as a ligand, allowing iron to be sequestered and transported into the cell. In recent times, this characteristic has gotten a lot of attention, and the in vitro assessment of siderophore synthesized by identified PGPR has been reported (Parray et al. 2016). Rather than Gram-positive PGPR transport systems, siderophore-mediated iron transfer mechanisms are best researched in Gram-negative PGPR transport systems. Among different varieties of 500 siderophores, only 270 have been structurally studied. Siderophores have been proposed as an environmentally acceptable alternative to insecticides.

Since siderophores have a higher affinity for iron than fungal pathogens, they have a competitive edge when it comes to effectively reducing the proliferation of phytopathogen (Govindasamy et al. 2008). When there is a lack of iron, fungal pathogens become unable to reproduce and are pushed out of their biological habitat. As a result, siderophore synthesis is an attractive feature of PGPR as a biocontrol agent. Siderophores produced by *Pseudomonas* are reported to have a stronger affinity than other bacterial siderophores (Patel et al. 2018). Several studies have been published on the biocontrol efficacy of PGPR that produce siderophores. Siderophore-producing strains of *B. subtilis* MF497446 and *P. koreensis* MG209738 exhibited strong effectiveness against the fungal pathogens, reduced the disease incidence and improved the crop growth (Ghazy and El-Nahrawy 2021). Under field circumstances, Attia et al. (2020) found that siderophore-producing PGPR strains, viz. *Lysinibacillus fusiformis* L-2, *Bacillus subtilis* B-1 and *Achromobacter xylosoxidans* A-3 suppressed the early blight disease of tomato caused by *Alternaria solani*. Similarly, the indigenously isolated *Pseudomonas* strain reduced the incidence of fusarium wilt disease in tomato crops by producing siderophore (Arya et al. 2018). In addition, siderophore-synthesizing *Streptomyces* SNL2 reduced the prevalence of wilt disease by 88.5% (Goudjal et al. 2016).

15.6 Future Perspective

Managing sustainable natural reserves can help ensure food security for the world's growing population. PGPB have been shown to play an important function in agricultural management in several studies. Though, there is still a knowledge vacuum underpinning microbe-plant symbiosis under various stress circumstances, especially pathogen stress. Understanding the rhizosphere ecology that governs pathogen and antagonist dispersion could help improve biocontrol efficiency against plant-based pathogens. Future studies will necessitate intense rhizosphere engineering based on the successful discovery and separation of novel metabolites, which could establish a unique environment for plant-microbe interactions. Instead, exploring and applying the combined inoculation over a single strain, on the other hand, could be an efficient means for the suppression of fungal diseases. Furthermore, genetic alterations to improve biocontrol values could be a new study area for managing plant diseases. Transforming the strains with higher quantities of antifungal and growth-promoting essential metabolites, for example, maybe an excellent option. The use of cutting-edge tools to explore microbiological, biochemical and molecular interactions between plants and interacting microorganisms may provide in-depth knowledge for a better understanding of interactions between plants and microbes. To summarize, the forthcoming challenge will be to improve the effectiveness and long-term resilience of biological control in the field. If this issue is handled, biocontrol efficacy could be increased by leveraging expertise to design better screening processes, formulations and application procedures, as well as innovative integrated disease management strategies.

15.7 Conclusions

Tomato is a highly nutritious vegetable crop grown all over the world and ranks second only to potatoes in terms of consumption. Tomato seed-borne infections, on the other hand, are a major source of concern in the seed industry because they have a negative impact on seedling germination and vigour, resulting in a significant reduction in yield and product quality. The current research shows that PGPR not only have different biological promotional effects on tomato plant development parameters but also operate as biocontrol agents (BCAs) to protect the plant from diseases. It should become increasingly more effective and cost-effective to replace fungicides with a biological pesticide. Before commercialization, molecular analysis can help stabilize the effects of PGPR in biological control and determine potential risks. To use PGPR effectively for disease reduction or crop protection in the future, a logical selection of organisms will be required, as well as technical improvements in upscaling and formulation procedures will be needed. The PGP genomic products may be enhanced through the genetic engineering of PGPR. As a result, a single bacterial strain or a consortium with varying features will reduce pathogen attacks while also promoting plant growth, which will stimulate producers. Although investigations should focus on the relative contributions of each mechanism responsible for PGPR strains' significant biocontrol activity, it has become obvious that they use numerous pathways to operate as an effective biocontrol agent. An in-depth study of microbial interactions with plants, as well as exploitation of microbial ecology in the soil and rhizosphere, will aid in revealing the many dimensions of disease suppression by these biocontrol agents. Furthermore, for maximal commercial utilization of these strains, cautiously conducted skilful field trials of tomato plants inoculated with BCAs are required. Finally, the success of the microbial inoculant industry, particularly those that use PGPRs, will be determined by factors such as product marketing and substantial research. Furthermore, to incorporate PGPR strains into the agriculture industry, they will need to be optimized for improved fermentation and formulation procedures.

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