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Review

Eco-smart biocontrol strategies utilizing potent microbes for sustainable management of phytopathogenic diseases

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ABSTRACT

Plants have an impact on the economy because they are used in the food and medical industries. Plants are a source of macro- and micronutrients for the health of humans and animals; however, the rise in microbial diseases has put plant health and yield at risk. Because there are insufficient controls, microbial infections annually impact approximately 25 % of the world's plant crops. Alternative strategies, such as biocontrol, are required to fight these illnesses. This review discusses the potential uses of recently discovered microorganisms because they are safe, effective, and unlikely to cause drug resistance. They have no negative effects on soil microbiology or the environment because they are environmentally benign. Biological control enhances indigenous microbiomes by reducing bacterial wilt, brown blotch, fire blight, and crown gall. More research is required to make these biocontrol agents more stable, effective, and less toxic before they can be used in commercial settings.

1. Introduction

The biocontrol approach has grabbed the attention of worldwide plant pathologists after an abrupt increase in plant diseases in the absence of limited antimicrobial methods [1]. It is estimated that 25 % of the world's plant crops are affected by pathogenic microorganisms that led to a sharp decline in crop yield, involving a significant portion of the world's crops each year [2] - plants comprised of several micronutrients and macronutrients which are the central part of human and animal health. Plants are also used for food and medicinal purposes due to limitless sources of phytomedicines [2,3]. 2020 was declared the universal year of plant health [4]. It is essential to protect plants from diseases to ensure food security [5]. For the past few decades, plant health has been dramatically threatened by phytopathogens that significantly reduce crop yield [6]. The widespread antimicrobial resistance in phytopathogenic microorganisms and their associated infections have massively stressed agriculture. Agriculture largely relies on chemical-based control measures and antibiotics, adversely affecting plant health and soil microbial flora [7].

Conversely, infected plants also carry pathogenic microorganisms and spread them to consumers, leading to foodborne illnesses [2]. Foodborne diseases affect about 600 million people across the globe [8]. Plant diseases are a significant player in the emergence and spread of foodborne diseases [2]. In the United States, for the past ten years, more than half of foodborne illnesses have been associated with plant foods [9]. In addition, it also gave rise to antibiotic-resistant phytopathogens, which are a severe concern [10,11].

These consequences cause alarming situations and give signals for

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alternative effective and eco-friendly approaches such as biocontrol to control plant diseases. Biological control was discovered by experimental methods in agriculture before the term itself came into use. They are more beneficial as they inhibit phytopathogens and may enhance plant growth [12]. Understanding the environmental behavior of biocontrol agents in disease management is necessary to introduce the most effective and specific biocontrol agent against a particular pathogen [13]. There are three methods of biocontrol: classical, conservational, and augmentative. The "classical" origin of application is the introduction of non-indigenous natural entities to control the pests, the enhancement of the natural and native entities to control pests is the "conservational" method, while the introduction of Indigenous natural enemies to reduce pests is "augmentative" method [14].

This review summarized the emerging bacteria, fungi, and bacteriophages with biocontrol potential and their applications against major essential plant diseases.

2. Plant diseases and their control

The overall agricultural production of harvests has been essentially diminishing by plant diseases, which are mainly brought about by pathogenic microbes assessed to cause 36 % of plant crops to be reduced because of plant diseases. Climate change also significantly influences plant disease dynamics since it affects the entire triangle of the plant diseases involved in disease cause and spread [15]. The pathogen's distribution in soil includes geographical range, niche preference, virulence, and, importantly, their interactions with environmental factors [16]. The main approaches include the practice of crop rotation, proper irrigation, and chemical treatment. Chemical and physical controls can be expensive, especially for small-scale farmers or in developing countries [17,18]. Antibiotics to treat plant diseases are chosen, considering their ability to fight specific pathogens and their safety for plants, people, and the environment. They are typically applied as foliar sprays or through irrigation systems [19]. However, most antibiotics are not used explicitly for any particular plant pathogenic bacteria, which leads the bacteria to develop resistance. Physical control is also one of the strategies to avoid plant diseases; it's done using solar heat for soil sterilization, effective management of pathogens, or application of controlled temperature to plant material and seed so that these organisms can be killed without harm to a plant. In the fight against plant diseases, it is also essential to adapt irrigation practices to limit excessive moisture [20].

Bacteria, fungi, and phages are frequently used as biocontrol agents to control plant diseases. These biocontrol substances are environmentally friendly and can be employed more effectively than chemical pesticides. Depending on the target bacteria disease and crop, their use may differ between soil treatment and foliar spraying [21]. Compared to chemicals, biocontrol agents are more effective against plant diseases and less associated with toxicities [22]. Table 1 shows the common advantages and disadvantages of conventional and biocontrol strategies to avoid plant-related pathogens.

Conversely, all these chemical and antibiotics-based strategies become ineffective due to inappropriate and extensive use given the emergence of antibiotics and chemical-resistant bacteria. In this regard, a biocontrol strategy is strongly recommended. Bio-control offers many promising advantages. Most importantly, it inhibits the targeted pathogens without influencing the microbial flora (non-host) in soil crucial for plant growth [23]. Biocontrol, biopesticides, and bio-stimulants are, in one way or another, related. Bio-stimulants enhance plant health by making it less susceptible to pest diseases (Fig. 1).

Table 1
Various advantages and disadvantages of chemical and other approaches versus biocontrol strategies against plant diseases.

	Advantages	Disadvantages
Chemical strategies	Rapid action	May pose health risks for farmers, workers, and consumers
	High availability	Harm beneficial organisms
	Easy synthesis	Prolonged exposure has long-term health effects, including cancer and neurological disorders.
	Easy production and use	Expensive
		Negatively affect soil quality and fertility and reduce agrobiodiversity.
	Easy application	Chances of antibiotic resistance
		The agriculturally important antibiotic efficacies have been reduced because of their imprudent use.
		Harm beneficial organisms like pollinators and natural predators of nuisances.
Biocontrol	Safe and sustainable and do not leave harmful residues in the environment	Susceptible to environmental factors
	Biocontrol agents are selective in their action.	Scale productions limitations
	Biocontrol agents can establish themselves in the field for a long time.	
	Biocontrol agents are cheaper than chemical pesticides in the long run	Not highly promoted
	Easy to inoculate and manipulate biological agents	Not easy to use
	Biocontrol agents can be integrated with different pest management strategies.	Strict regulation criteria
	Develop disease resistance in plants.	
	Fixation of atmospheric nitrogen	
	Several modes of biocontrol agent applications	
	Phages are considered safe and eco-friendly.	
	There has been no evidence of adverse effects of phages.	
	Broad spectrum activity of the phage cocktails	Negligible chances of resistance

3. Biocontrol agents for disease management

3.1. Bacterial agents

Generally, plant diseases are caused mainly by bacteria; however, some bacteria can control plant diseases caused by different agents [24]. Plant growth performance is related to the presence of specific bacterial endophytic organisms. Research has identified vital genera, including *Micrococcus, Serratia, Bacillus, Curtobacterium, Pseudomonas, and Arthrobacter,* as endophytic candidates contributing to this phenomenon [25]. As a result, these microorganisms have garnered significant attention in recent years due to their impressive execution in observational systems [25]. Nevertheless, traditional methods of studying these microorganisms have limitations. Recent progress in molecular techniques now enables a genetic screening approach, allowing scientists to explore previously unstudied traits and unlock the full potential of these beneficial bacteria. This breakthrough opens up new avenues for research and application, paving the way for improving innovative strategies to enhance plant maturation and productivity.

Several bacteria like *Bacillus* spp, *Pseudomonas* spp, and *Streptomyces* species are used as biocontrol agents. The non-pathogenic strain of *Streptomyces* can reduce the symptoms of pathogenic *Streptomyces* induced-potato scabs disease [26]. Root-knot nematode infestation is successfully treated using the bacillus isolates [27]. Bacillus species, such as *Bacillus atrophaeus*, especially those with biocontrol potential, inhibit the nematodes (Meloidogyne incognita) by producing reactive oxygen species [28]. Ding et al., 2013 conducted experiments of pot and

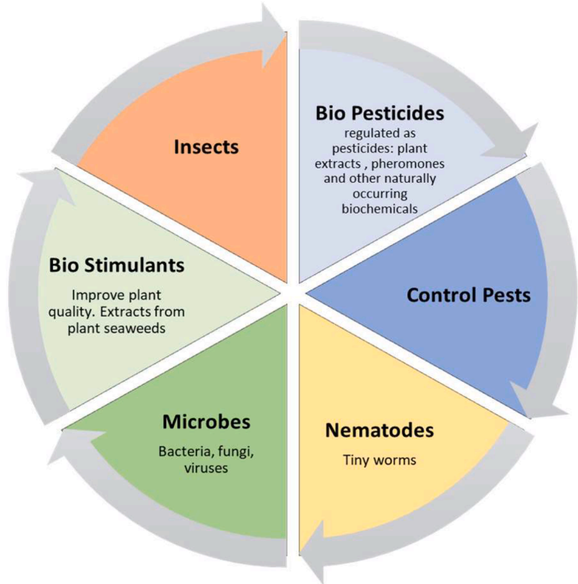

Fig. 1. Biocontrol controls pests using insects, nematodes, and various microbes (bacteria, fungi, and viruses). Some microbes can also be used as bio-stimulants.

field to evaluate the *Bacillus subtilis* and *Bacillus amyloliquefaciens* strains and their derivative bioorganic fertilizers BIO36 and BIO23 as potential biocontrol agents against bacterial wilt disease of potato [29]. Bacteria with biocontrol potential reduce the nematode's population by affecting its feeding and reproduction. Several species of Trichoderma potentially showed biocontrol against deadly pathogenic phytopathogens. *Trichoderma hamatum* LU593 reduces the severity of *S. sclerotiorum* disease in cabbage by reducing apothecial production [30]. Similarly, another species of Trichoderma called T. asperellum decreases the infection symptoms of S. sclerotiorum in field trials of beans through antagonistic activity [31] Trichoderma spp is also effective in the reduction of several fruits, including mangoes, okra, onion, and other economically significant diseases. The *Pseudomonas fluorescence* inhibits the rot potato pathogens by producing antibiotic 2,4 diacetyl-phloroglucinol [32]. Various *P. fluorescence* metabolites such as Hydrogen cyanide, oligomycin A, oomycin A, and zwittermycin A are reported to control fungal pathogens [33]. *P. fluorescens* + *P. lilacinus* also reported reducing the nematode population in soil, root, and tuber [24]. Rhizobial isolates are highly active against plant pathogenic fungi, including *Fusarium oxysporum, Macrophomina phaseolina, Rhizoctonia solani, and F. solani* associated with mungbean crop diseases. The phytopathogen *Colletotrichum capsici* which causes anthracnose on the chilli plant, is reported to control by using *Pseudomonas aeruginosa* [34]. *Bacillus megaterium* showed antagonistic activity against blue mold, which affects citrus fruit [35]. *Bacillus thuringiensis* protects. *Brassica campestris* L suppresses its pathogen known as S. sclerotiorum growth by inducing systemic resistance [36]. Recently, Bacillus velezensis DMW1 was reported to show antagonistic activity in vitro and pot experiments against *Phytophthora sojae* and *Ralstonia solanacearum* in the case of tomato and soybean plants [37]. *Bacillus Subtilis* ATCC6633 are used as biocontrol agents to control disease of Wheat and Maize caused by *Fusarium graminearum* and *Fusarium verticillioides* by antagonism [38].

The bacterial enzyme cellulase has been reported to control plant pathogenic fungi such as *Phytophthora cinnamomic* by rupturing their cell wall [39]. *Bacillus cereus* produces antimicrobial enzymes called chitinolytic enzymes that have shown significant inhibitory effects against the fungal pathogen *Rhizoctonia solani,* which causes various diseases in plants [40]. Bacteria-based biocontrol strategy has been successful in multiple devastating plant diseases, including fire blight, crown gall disease, and brown blotch. Fire blight is one of the most common diseases that has infected several plants, such as apples, hawthorn, and pears, for over 200 years [41]. The causative agent of fire blight disease bacterium *Erwinia amylovora* can infect blossoms, fruits, vegetative shoots, woody tissues, and rootstock crowns. The control and treatment of fire blight disease are challenging, as it rapidly spreads in the plant [42]. Microbial bio-control of the blossom blight is an effective strategy to control this disease [43]. Most studies on the biological control of fire blight focused on two species of epiphytic bacteria: *Erwinia herbicola* and *Pseudomonas fluorescens* [43]. *Pseudomonas* spp has potential use in biocontrol and *P. agglomerans* strain, E325, which has shown promising antagonism against *E. amylovora* in the laboratory and field and is already commercially available. One commercially available strain of *Pseudomonas fluorescens* is A506 for managing fire blight disease [43]. *P. fluorescens* strain A506 and Pan-toea agglomerans strain C9-1 also showed inhibitory effects against *E. amylovora* [43]. *P. fluorescens strain* A506 and *Pantoea agglomerans* strain C9-1 are less resistant to high sugar concentrations than *E. amylovora* strain EA153. Thus, it can fire blight disease due to higher resistance to a high sugar-rich environment. Several mechanisms have been proposed for these biocontrol agents, such as producing toxic aglycones, induction of a phytoalexin-like compound, competition for nitrogen, and production of an antibiotic-type molecule [44].

P. fluorescens strain PfA506 decreases frost injury and fruit russeting by suppressing populations of ice-nucleation active and auxin-producing microorganisms, respectively. *P. fluorescens* strain PfA506 is effective when employed three days before the pathogen inoculation; however, it doesn't inhibit the pathogen when applied in co-inoculation [45]. It has been observed that *P. fluorescens* strain PfA506 produces putative β-glucosidases that react with the glycoside, arbutin, and other phenolics in pear tissues, resulting in *E. amylovora* inhibition [45]. *E. amylovora* is also reported to be inhibited by other bacteria, such as *Pantoea vagans* C9-1 and *Pantoea agglomerans*. These bacteria were reported to inhibit *E. amylovora*-induced fire blight disease by producing antimicrobial compounds such as herbicolin O and herbicolin I [43]. The deadly pathogenic and widely distributed bacteria *Agrobacterium tumefaciens* was reported to be readily controlled by antagonistic bacteria such as the *nontumorigenic* strain *Agrobacterium radiobacter* K84, particularly in the case of crown gall disease [46,47]. *A. tumefaciens* is a soil-borne bacterium that affects more than 1000 different dicotyledonous economically essential plants [48]. *A. tumefaciens* can be controlled by agrocins produced by the antagonistic bacterium *R. radiobacter* K84 [46]. It has been found that *R. radiobacter* K84 produces antimicrobial compounds that inhibit a subset of pathogenic strains of *A. tumefaciens* by targeting leucyl-tRNA synthetase [49]. Brown blotch is a mushroom disease caused by *Pseudomonas tolaasii* [50]. Due to higher economic value and domestic consumption, the production of mushrooms surpasses 500 million tons yearly. However, their production is considerably troubled by brown blotch disease [51]. It mainly infects the economically significant cultivated mushrooms and causes deterioration of freshly harvested mushrooms, which is responsible for significant crop losses [51]. Antagonistic bacteria such as Mycetocola can control the growth of *P. tolaasii* by cleaving the tolaasin [52] and suppressing brown botch disease. Mycetocola cleaves the tolaasin by secreting enzymes that convert it into the inactive linear form of the molecule. The antagonistic activity of bacteria-based biocontrol agents such as B. velezensis is produced by their secondary metabolites such as fencing and lipopeptides surfactin. Such antagonistic effects of B. velezensis were observed against R. solanacearum and Fusarium oxysporum [31].

Some researchers employ beneficial bacteria to protect plants from phytopathogens by developing disease resistance [31]. Also, they reduce the population of phytopathogens by making biofilms and creating plant–microbial interactions in the rhizosphere region [53]. In plants, systemic resistance is induced by biocontrol bacteria through several enzymes, including polyphenol oxidase, phenylalanine ammonia-lyase (PAL), chitinase, and peroxidase. *B. subtilis* secreted chitinases showed significant antifungal potential by reducing the disease incidence by 20–35 %. Fig. 2 shows some direct and indirect biocontrol mechanisms of action shown by many bacterial species.

Sometimes, atmospheric nitrogen is unavailable for plants and must be fixed by external factors, including bacteria such as *B. subtilis*, which also helps nodulation by other bacteria, resulting in colonizing native symbiotic rhizobacteria [54]. Chitosanase, protease, glucanase, and cellulase enzymes of Bacillus spp were reported to distort fungal hyphae after attachment to mycelial cell walls [55]. Hyphae distortion and spore germination inhibition are done by volatiles produced by *Bacillus* in a contact-independent manner on agar plates [56]. Bacillus reduces the pathogen virulence by interfering with quorum sensing (QS). For example, an enzyme produced by AiiA inactivates QS autoinducers. Such a mechanism was reported to control the *E. carotovora* associated with potato soft rot disease [54]. The biocontrol *Pseudomonas* also produced secondary metabolites such as phenazines having antimicrobial and insecticidal potential. 2,4-diacetyl phloroglucinol (DAPG) is a well-conserved antimicrobial compound produced by *P. protegens* and *P. corrugata*, also known as polyketide antibiotic having broad spectrum antimicrobial potential including antibacterial, antifungal, and also effective against nematodes and oomycetes [54,57]. Antagonism is one of the widely known antimicrobial mechanisms of *Pseudomonas* sp metabolites. The frequently producing antimicrobial metabolites by *Pseudomonas* sp with antimicrobial potential are 2,4-diacetyl phloroglucinol (DAPG), pyoluteorin, Hydrogen cyanide (HCN), Rhizoxins, which are generated by a few isolates of *P. protegens* and *P. chlororaphis* MA342, lipopeptide sessilin, promysalin, l-puromycin [54]. These metabolites were reported to show biocontrol potential against several phytopathogens.

Furthermore, the isolate *Pseudomonas* DFs831 has demonstrated exceptional performance as an individual treatment, except for controlling angular leaf spots. Previous studies have also highlighted the efficacy of the combination C01, comprising two *Bacillus cereus* isolates (DFs093 and DFs769) and one *Pseudomonas fluorescens* isolate (DFs831), in controlling various plant pathogens [58]. Notably, these isolates possess lipolytic, proteolytic, and chitinolytic activities and produce ammonia and antibiotics, showcasing their potential as biocontrol agents. Plant growth performance is related to the presence of specific bacterial endophytic organisms. Research has identified vital genera, including *Micrococcus, Serratia, Bacillus, Curtobacterium, Pseudomonas,* and *Arthrobacter,* as endophytic candidates contributing to this phenomenon. As a result, these microorganisms have garnered significant attention in recent years due to their impressive execution in observational systems [59]. Studies have confirmed the efficacy of *Collimonas fungivorans* as a biocontrol agent against *Fusarium oxysporum f. sp. radicis-lycopersici,* which causes tomato foot and root rot. Although the exact mechanism of action is still unknown, research suggests that competition for resources and niches is a crucial factor [60] (Table 2).

3.2. Fungal agents

Beneficial fungi produce many bioactive compounds that have gained significant attention for sustainable agriculture as biocontrol agents. These agents potentially aid in the fight against various soil and airborne plant pathogens [62,63], reducing farmers' reliance on chemical pesticides. Many beneficial fungi inhibit the growth of different plant pathogens (Table 3). In recent years, the increasing demand for environmentally friendly and organic agricultural practices has driven research, mainly focusing on fungi that have the potential to neutralize pathogens or enhance plant defenses directly. Endophytic fungi are a rich source of novel secondary metabolites that can potentially have various agricultural applications. The thirst for fungal-based biocontrol agents has increased considerably because of target specificity, comparatively high reproductive rate, and a short generation time [64]. Parasitic fungi are emerging as potential biocontrol agents that can shift their mode of parasitism to saprotrophic [64]. *Trichoderma, Aspergillus*, and *Penicillium* are the most widespread fungal genera used as fungal-based biocontrol agents against bacterial and fungal plant diseases [31]. *Trichoderma* is a substantial biocontrol agent [64] against foliar, root, and fruit diseases in plants and controls invertebrates such as nematodes [65]. Gliotoxin is an antimycotic compound excreted by *Trichoderma* species that is poisonous to several plant pathogens [66]. Various researchers have reported the beneficial properties of the *Trichoderma* strain's bio-stimulation, biofertilization, and plant protection [13,67]. Henry et al. suggested that siderophore producers are potential biocontrol agents which are also effective against bacteria. It outcompetes cyanide-producing bacteria in the rhizosphere [68]. Fungal biocontrol agents employ various mechanisms to antagonize the effect of pathogens, including mycoparasitism, competition for nutrients and space, induction of plant systemic resistance, and production of antimicrobial compounds [69]. Mycoparasitism is the primary type of antagonism that involves direct physical interaction or parasitism with the host mycelium [70]. Trichoderma species are among the most studied fungal BCAs due to their ability to control a wide range of plant pathogens, including species of Fusarium, Rhizoctonia, and Sclerotinia [71]. Chitinases produced by the Trichoderma spp. Interact with and

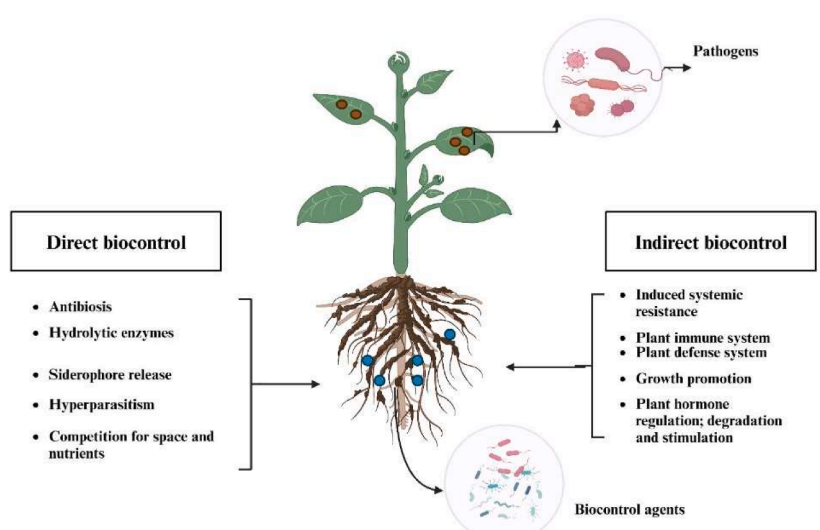

Fig. 2. Modes of action of bacterial biocontrol against plant pathogens to manage the diseases and induction of several benefits to the plant.

Table 2
Bacterial biocontrol agents, target pathogens, and mechanisms of action.

Bacterial species/ Genus	Target pathogens/Diseases	Mechanism of action	Applications/Observations	Reference number
Bacillus atrophaeus	*Meloidogyne incognita* (root-knot nematode)	Production of reactive oxygen species	Inhibits nematodes by producing ROS.	[27]
Bacillus subtilis	*Fusarium graminearum, Fusarium verticillioides*	Antagonism, chitinase production	Used as a biocontrol agent for wheat and maize diseases.	[37]
Bacillus cereus	*Rhizoctonia solani*	Chitinolytic enzyme production	Significant inhibitory effects against fungal pathogens.	[39]
Bacillus megaterium	Blue mold on citrus	Antagonistic activity	Protects citrus fruits from blue mold.	[34]
Bacillus thuringiensis	*Sclerotinia sclerotiorum* on *Brassica campestris*	Induction of systemic resistance	Suppresses pathogen growth in Brassica plants.	[35]
Bacillus velezensis DMW1	*Phytophthora sojae, Ralstonia solanacearum*	Antagonistic activity in vitro and pot experiments	Effective against tomato and soybean pathogens.	[36]
Pseudomonas fluorescens	Potato rot pathogens, fire blight (*Erwinia amylovora)*	Antibiotic production, inhibition of ice-nucleation active microorganisms	Inhibits rot pathogens, reduces frost injury, and controls fire blight in pears.	[42,44]
Pseudomonas aeruginosa	*Colletotrichum capsici* (chilli anthracnose)	Antagonistic activity	Controls anthracnose in chili plants.	[33]
Pseudomonas tolaasii	Brown blotch on mushrooms	Antagonistic bacteria (*Mycetocola*) cleave tolaasin	Controls brown blotch disease in mushrooms.	[49,51]
Pantoea agglomerans	Fire blight (*Erwinia amylovora*)	Production of antimicrobial compounds (herbicolin O and I)	Commercially available strains (E325, C9-1) for fire blight control.	[42]
Agrobacterium radiobacter K84	Crown gall disease (*Agrobacterium tumefaciens*)	Production of agrocins	Effective against *A. tumefaciens* in crown gall disease.	[45,48]
Trichoderma hamatum LU593	*Sclerotinia sclerotiorum* disease in cabbage	Reduction of apothecial production	Reduces disease severity in cabbage.	[29]
Trichoderma asperellum	*Sclerotinia sclerotiorum* in beans	Antagonistic activity	Decreases infection symptoms in field trials of beans.	[61]
Collimonas fungivorans	*Fusarium oxysporum* f. sp. radicis-lycopersici (tomato foot and root rot)	Competition for resources and niches	Confirmed as a biocontrol agent against tomato foot and root rot.	[60]
Pseudomonas spp. (DFs831)	Angular leaf spot	Lipolytic, proteolytic, chitinolytic activities; ammonia and antibiotic production	Shows exceptional performance as an individual treatment, especially in combination with other biocontrol agents.	[58]
Pseudomonas protegens, P. corrugate	Various phytopathogens	Production of 2,4-diacetyl phloroglucinol (DAPG)	DAPG acts as an antimicrobial with a broad spectrum, including antibacterial, antifungal, and activity against nematodes and oomycetes.	[53,57]
Rhizobial isolates	*Fusarium oxysporum, Macrophomina phaseolina, Rhizoctonia solani, F. solani*	Highly active against plant pathogenic fungi	Associated with disease control in moonbeam crops.	[33]
Pseudomonas fluorescens + *P. lilacinus*	Nematodes in soil, root, and tuber	Reduction of nematode population	Combined use reduces nematode populations.	[23]
Erwinia herbicola, Pseudomonas fluorescens	Fire blight (*Erwinia amylovora*)	Antagonistic epiphytic bacteria	Effective in controlling fire blight disease through microbial biocontrol of blossom blight.	[42]

degrade chitin in the cell wall.

Similarly, glucanase, another enzyme produced by the same species, hydrolysis the glycosidic bonds in polysaccharides of the pathogenic fungi, ultimately leading to the disintegration of the phytopathogenic cell wall [72]. Xylanase enzyme extracted from *Trichoderma harzianum* exhibits inhibitory effects against several plant pathogenic fungi, including *Corynespora cassiicola, Alternaria alternata, Fusarium oxysporum*, and *Botrytis fabae* [73]. Additionally, the mycoparasite *T. asperellum* targets *Globisporangium ultimum* NZW by coiling around its hyphae, leading to damage, fragmentation, and degradation of *G. ultimatum* NZW [74]. Treatment with *Trichoderma* resulted in a significantly higher leaf count, plant height, vegetative weight, and root weight. Therefore, using this antagonistic microorganism could be a viable substitute for farmers who prioritize plant quality and environmental sensitivity during the cultivation cycle of ornamental and horticultural plants, making the best use of fertilizers that minimize the use of other products used for plant protection [75]. The non-pathogenic strains of *F. oxysporum* have been reported to inhibit fungal pathogens either directly through antagonism or induce pathogens resistance in the host plant by activating their defense [76]. Following the activation of defense mechanisms, plants produce hydrolytic enzymes such as glycosidases and chitinases as secondary metabolites, which inhibit fungal growth [77].

Competition for nutrients and space is another crucial strategy through which these biocontrol agents suppress pathogens. This strategy involves rapidly colonizing the plant rhizosphere or phyllosphere by the biocontrol fungus, effectively producing a challenging competition with pathogens for niches and nutrients. For example, the fungus *Pythium oligandrum* has been shown to outcompete pathogenic *Pythium* species by colonizing the root surfaces of plants and utilizing available nutrients more efficiently [78]. *P. oligandrum* promotes plant growth in *Medicago truncatula* and *Pisum sativum* to protect them against infection by the oomycete *Aphanomyces euteiches*, a devastating legume root pathogen [79]. *Pythium oligandrum* is a typical and widely distributed soil-habitant fungus [78]. It is also reported to increase plant growth by enhancing the auxinic pathway and plant resistance to diseases by stimulating plant defense systems [80]. *P. oligandrum* controls the growth of *Ralstonia solanacearum*-induced bacterial wilt. A homogenate of its mycelia demonstrates elicitor activity, generating an ethylene (ET)–dependent defense response [81]. The antagonistic fungus produces elicitin-like proteins, which induce resistance to plants and make them less susceptible to plants. An elicitin-like protein called oligandrin causes cytological and biochemical changes in tomato cells, leading to the development of resistance to *Phytophthora parasitica* [81].

The fungal biocontrol agents may display parasitism, antibiosis, competition for nutrients and space, the ability to prevent the pathogen from colonizing specific host tissues, and induction of resistance in plants against diseases [82]. Induction of systemic resistance in plants is a highly effective but indirect method employed by specific fungal-based bio-control agents. Beneficial interaction of members of the fungal genus *Trichoderma* with plant roots primes the plant immune system, promoting systemic resistance to pathogen infection [83]. The interaction

Table 3
Fungal biocontrol agents, target pathogens, and mechanisms of action.

Fungal species/Genus	Target pathogens/Diseases	Mechanism of action	Applications/Observations	Reference number
Trichoderma harzianum	*Corynespora cassiicola, Alternaria alternata, Fusarium oxysporum, Botrytis fabae*	Production of xylanase, mycoparasitism	Inhibits various plant pathogenic fungi and improves plant growth parameters.	[73,75]
Trichoderma asperellum	*Globisporangium ultimum* NZW	Mycoparasitism, coiling around hyphae, degradation of pathogen	Targets and degrades G. ultimatum NZW, improving plant quality.	[74,75]
Trichoderma spp.	*Fusarium* spp., *Rhizoctonia* spp., *Sclerotinia* spp.	Production of chitinases, glucanases, induced systemic resistance	Controls a wide range of plant pathogens, enhances plant immune system, and promotes systemic resistance.	[71,83,84]
Pythium oligandrum	*Pythium* species, *Ralstonia solanacearum*	Competition for nutrients and space, production of elicitin-like proteins	Outcompetes pathogens, promotes plant growth, induces resistance in plants, and controls bacterial wilt.	[78,79,81]
*Fusarium oxysporum (*non-pathogenic strains*)*	Various fungal pathogens	Antagonism, induction of pathogen resistance	Inhibits fungal pathogens directly or by inducing host plant defenses.	[76,77]
Arbuscular Mycorrhizal Fungi (AMF)	Various plant pathogens	Competition for resources, alteration of root morphology, production of secondary metabolites	Inhibits pathogen growth, enhances root development, and induces plant resistance.	[86,87,90]
Piriformospora indica	Bacterial wilt in tomato	Biocontrol activity	Acts as a biocontrol agent against bacterial wilt in tomato plants.	[96]
Saccharomyces spp., Gliocladium spp.	Various plant pathogens	Production of antibacterial compounds, antagonism	Exhibits antagonistic properties against a range of diseases, producing antimicrobial compounds.	[93,95]
Trichoderma virens	*Pythium ultimum, Rhizoctonia solani, Rhizopus oryzae*	Production of glucanases, genetic modification for enhanced biocontrol	Genetically modified strains show increased suppression of diseases and enhanced biocontrol activity.	[103,105]
Aspergillus spp., *Penicillium* spp.	Various bacterial and fungal plant pathogens	Production of bioactive compounds	Popular fungal genera are used as biocontrol agents against both bacterial and fungal plant diseases.	[61,63]
Trichoderma spp. + *Bacillus subtilis*	Soil-borne diseases in tomato crops	Synergistic effect, enhanced pathogen suppression	The combination strategy provides superior control of soil-borne diseases compared to individual agents alone.	[107]

of Trichoderma species with plant roots has also been reported to enhance induced systemic resistance in plants by boosting the activity of defense-related enzymes like polyphenol oxidase, peroxidase, and phenylalanine ammonia-lyase (PAL), as well as by influencing root exudates and modifications, including amino acids and polysaccharides [84]. Trichome produces defense-related compounds such as phytoalexins and pathogenesis-related proteins and non-ribosomal peptides, aromatic compounds, and heterocyclic metabolites that help fortify the plant against subsequent pathogen attacks [85].

Yeasts have antagonistic activity and different mechanisms of action, indicating that they could be attractive candidates for developing biocontrol agents. *Arbuscular Mycorrhizal* fungi (AMF) are reported to inhibit the growth of plant pathogens through direct effects, such as competition for resources or space, or indirect effects associated with plants [86]. Yet, the mechanism may also vary according to the specific AMF-pathogen-plant interaction. Studies have suggested that the increased root branching in mycorrhizal plants helps avoid pathogens and has potential consequences for pathogen infection [87–89]. The symbiosis with AMF has the power to alter the root system and morphology of plants by causing them to develop, produce more branches, have thicker epidermis at the root tip, and have more cell layers. These modifications delay the pathogen's initial infection [90, 91]. AMF can also produce chemicals, including phytochemicals, calluses, alkaloids, and phenols, on the surface of the inner and outer hyphae of the root. Plants benefit from these secondary metabolites by using them for their purposes, such as to develop resistance [92].

Beneficial fungi produce many bioactive compounds that can be used as agrochemicals for crop protection. Fig. 3 displays the impact of various antimicrobial chemicals fungi produce on plant growth parameters and diseases as a biological control agent. It has also been documented those certain fungi, such as *Saccharomyces* and *Gliocladium*, have antagonistic properties against various diseases [84,93]. Production of anti-bacterial compounds such as antibiotics, volatile organic compounds, and lytic enzymes is also a common strategy among fungi. These

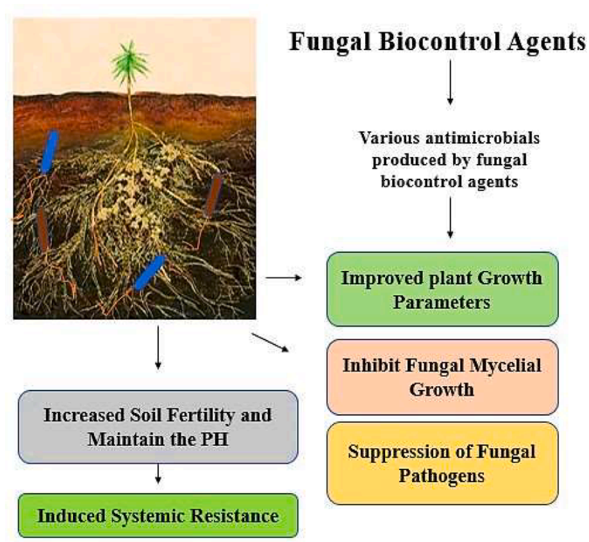

Fig. 3. Different antimicrobial compounds made by fungus and their effects on plant development parameters and plant diseases as a biological control agent. Fungi produce antimicrobial compounds with broad-spectrum antagonistic impact against various diseases and can induce systemic resistance.

compounds can inhibit or potentially destroy pathogenic microorganisms. For instance, *Trichoderma virens* produces gliotoxin, which has an inhibitory effect against various phytopathogenic fungi and soil-born bacteria [94]. Similarly, Trichoderma species produce a wide range of secondary metabolites, such as viridin and pyrones, which have low antibacterial activity but are potential biological pesticides. properties [95]. *Piriformospora indica,* a fungal root endophyte, is a potential biocontrol agent against bacterial wilt disease in two varieties of tomato

[96].

Endophytic fungi use mutualism and, in rare instances, parasitism to engage in intricate and close interactions with their hosts [97,98]. Because of their ability to produce a wide range of structurally different and physiologically active secondary metabolites, they are essential for shielding their hosts from harmful bacteria and pests [99]. Endophytic fungi have been found to produce a wide range of metabolites with different chemical structures, such as terpenoids, alkaloids, steroids, peptides, isocoumarins, benzopyranones, and quinones. The discovery of these metabolites gave researchers a strong chemical foundation for building agrochemicals with potential uses in agriculture, including those for herbicidal, nematocidal, insecticidal, antibacterial, and antifungal purposes [100]. Genetic approaches allow the exploration of fungal antagonists [101,102]. For instance, A strain of Trichoderma virens that released a combination of glucanases and showed significantly increased suppression of the diseases *Pythium ultimum* (*Oomycota, Chromista*), *Rhizoctonia solani*, and *Rhizopus oryzae* was produced by introducing numerous lytic enzyme-encoding genes into the genome of the organism [103,104]. Strain improvement of beneficial fungi through genetic modification and selective breeding has been a critical area of advancement. For example, researchers have developed genetically modified Trichoderma strains that exhibit enhanced chitinase production, resulting in increased biocontrol activity against root pathogens like *Phytophthora* spp [105]. The development of multi-functional strains that can simultaneously promote plant growth can serve particularly valuable in pest management by the farmers. Genetically improved stains can serve multiple roles, including disease suppression, nutrient mobilization, and tolerance against pathogen-induced stress [106].

Similarly, fungal bio-control agents and other beneficial microbial or chemical treatments can provide broader disease control. This combination strategy has been shown to often result in enhanced pathogen suppression and reduced disease incidence compared to the use of individual agents. For instance, combining *Trichoderma* with *Bacillus subtilis* has been reported to provide superior control of soil-borne diseases in tomato crops compared to either agent alone [107].

3.4. Phage-based agents

Phages are highly specific, which allows them to replicate in the presence of their host bacteria while ceasing to increase in the absence of these hosts. This reduces the impact on microbial ecosystems in both soil and the environments where they are applied [61]. Secondly, there has been no evidence of bacteriophage's adverse effects on the eukaryote cells in plants and animals up to this point [108]. Phage therapy has shown promising results against bacterial diseases in several economically important plants such as potato*es* [109], tomatoes [110], Grapevines [111], Onion [112], Lettuce [113], Radish [114], Grapefruit, Citrus [115], Leek [116], Mushrooms [117], pear, apple, Pepper [118], and Cherry trees [119]. The efficacy of phage therapy increases with phage cocktails, as co-inoculation of various phages such as 8D1, 8D2, 8D3, 8D4, 8D5, 8D7, 8D9, 8D10, and 8D11 significantly reduce the soft rot infection on potato slices up to 70 % [120]. The phage cocktails formulated with different stabilizers showed significant inhibitory effects against bacterial spot disease in tomatoes caused by *Xanthomonas campestris3 pv. Vesicatoria* [121]. Bacterial spot disease decreased by combining phage with plant activator (ASM) [122]. Das et al. reduce the growth of *X. fastidiosa* in grapevines by pre- and post-inoculation Sano, Salvo, Prado, and Paz used as a cocktail [111]. Phage therapy also showed promising results in reducing the soft rot disease caused by *Pectobacterium carotovorum ssp in lettuce. carotovorum* [113]. The combination of two phages, 8Ea1337-26 and 8Ea 2345, decreases the symptoms of infected detached pear tree blossoms by 84 % and 96 % caused by *Erwinia amylovora*. 8Ea1337-26 alone reduced the 54 % infection of potted apple tree blossoms [123].

Several bacteria infecting lytic phages can potentially reduce bacterial infections in plants and have been considered essential biocontrol agents [7,124–126]. After the emergence of antibiotic-resistant bacterial species and the decreasing efficacies of copper-based compounds, phage therapy has grabbed the attention of worldwide researchers. Compared to other antimicrobial agents, which disturb the microbial flora, interrupt the nutrient cycle, and ultimately cause nutrient deficiencies in soil, phages are considered safe and eco-friendly and comparatively have high efficacies [127–129]. Bacteriophages with lytic potential are extensively used to treat phytopathogenic bacterial diseases worldwide [31]. The bacteriophages were discovered by William Twort in 1915 for the first time. D'herelle reported the inhibition of bacteria with phages in 1917, which were thought of as a new biocontrol agent. The first bacteriophage-based biocontrol study was reported in 1924 [130]. In 1935, Thomas used phages against Stewart's wilt disease caused by *Pantoea stewartii* and discovered that the disease incidence was reduced significantly by applying phages to seeds before germination [131]. Since then, phage therapy has been considered a possible remedy for controlling phytopathogenic bacteria, triggering the researcher's interest in phage therapy [132]. The extracted metabolites from the damaged part of the plant showed inhibitory effects against the growth of *X. campestris pv campestris* [133]. Later, phages were identified in the extracted metabolites. After this work, the infected part of the plant was recognized as a source of phage, as the damaged part had a bulk of pathogens, and the phage was found near the host bacterium. Later, Kotila and Coons used a soil-isolated phage against *P. carotovorum*, which causes blackleg disease in potatoes, and observed that pathogen growth was inhibited with phages [131].

Moreover, the soft rot disease in carrots and potatoes caused by *P. carotovorum ssp carotovorums* and *Pectobacterium atrosepticum* have been treated and prevented by phage therapy [133]. 13 agriculturally important phytopathogenic bacteria associated with different diseases in different plant hosts have been successfully treated with phage therapy. *P. carotovorum* spp causes soft rot disease in potatoes, and disease severity was reduced with the bioassays of two phages, 8PD10.3 and 8PD23.1 [134]. *Dickeya solani* causes soft rot and blackleg diseases in potatoes; both disorders are reported to be reduced with phage therapy [120]. The phage reduced the surface lesions of a common scab from 23 % to 1.5 % in potatoes caused by *Streptomyces scabies* [135]. The bacterial wilt in tomatoes caused by *Ralstonia solanacearum* has been successfully treated with phage [110]. The bacterial spot disease caused by *X. campestris pv. vesicatoria* has been treated with phage cocktails (Table 4) [121].

Phage can be directly applied on the surface of infected plant flowers or coated with seeds. Also, it can be directly introduced in the soil, tailored to the crop's specific needs and the phytopathogen's nature. However, the phage application on the leaf surface may affected by dryness; therefore, it is ideally applied on blossoms [136]. Pages can also be directly applied to fresh-cut fruits and vegetables, such as melon slices [137]. The direct application of phages on plant surfaces is performed through phage spray, mainly used on aerial parts of plants, such as bacterial spots, blights, and cankers. Multiple doses of spraying are necessary to eradicate the pathogens, particularly persistent pathogens [138]. Fig. 4 shows the comparison of phage-treated plants with chemically treated plants.

Several phage biocontrol solutions have been available, including Agriphage (Registered in USA-EPA Reg. No. 67986-1) [142], which controls *Xanthomonas. campestris* pv. *vesicatoria* or *Pseudomonas. syringae* pv. Tomato. Other products are AgriPhage XCV and AgriPhage PST [143]. Erwiphage (Registered in USA-EPA Reg. No. 67986-8) is a Hungarian-based product used to manage fire blight *Erwinia amylovora* in apple trees. Furthermore, APS Biocontrol Ltd., a Scottish enterprise, has established Biolyse, a bacteriophage-based wash solution for potato tubers [126].

Table 4
Phage-based agents, target pathogens, and mechanisms of action.

Phage agent	Target pathogens/Diseases	Mechanism of action	Applications/Observations	Reference number
Phage cocktails (e.g., 8D1, 8D2, 8D3, etc.)	Soft rot in potatoes	Lytic activity against bacterial pathogens	Significantly reduces soft rot infection on potato slices by up to 70 %.	[123]
Phage cocktail (Sano, Salvo, Prado, Paz)	*Xylella fastidiosa* in grapevines	Pre- and post-inoculation phage treatment	Reduces the growth of *X. fastidiosa* in grapevines.	[113]
Phages 8Ea1337-26 and 8Ea 2345	Fire blight (*Erwinia amylovora*)	Lytic activity against bacterial pathogens	Decreases infection symptoms in pear and apple tree blossoms by up to 96 %.	[125]
Phage 8PD10.3 and 8PD23.1	Soft rot in potatoes caused by *P. carotovorum*	Lytic activity against bacterial pathogens	Reduces disease severity in potatoes.	[139]
Phages targeting Dickeya solani	Soft rot and blackleg diseases in potatoes	Lytic activity against bacterial pathogens	Reduces the incidence of soft rot and blackleg diseases.	[123]
Phages for Ralstonia solanacearum	Bacterial wilt in tomatoes	Lytic activity against bacterial pathogens	Successfully treats bacterial wilt in tomatoes.	[112]
AgriPhage (Omnilytics)	Bacterial spot (*X. campestris* pv. vesicatoria) on tomatoes and peppers	Lytic activity against bacterial pathogens	First phage-based biopesticide registered by the US EPA, effective against bacterial spots or specks on tomatoes and peppers.	[140,141]
Erwiphage (Enviroinvest)	Fire blight (*Erwinia amylovora*) in apple trees	Lytic activity against bacterial pathogens	Registered biopesticide for managing fire blight in apple trees.	[131]
Agriphage Citrus Canker™	Citrus canker (*Xanthomonas citri* subsp. citri)	Lytic activity against bacterial pathogens	Biopesticide for controlling citrus canker in various citrus fruits.	[131]
Agriphage CMM™	*Clavibacter michiganensis* subsp. michiganensis in tomatoes	Lytic activity against bacterial pathogens	Customizable phage formulation to target specific bacterial strains.	[131]
Biolyse (APS Biocontrol Ltd.)	Soft rot in potato tubers caused by Enterobacteriaceae	Lytic activity against bacterial pathogens	Bacteriophage-based wash solution used during storage to mitigate soft rot disease in potato tubers.	[131]

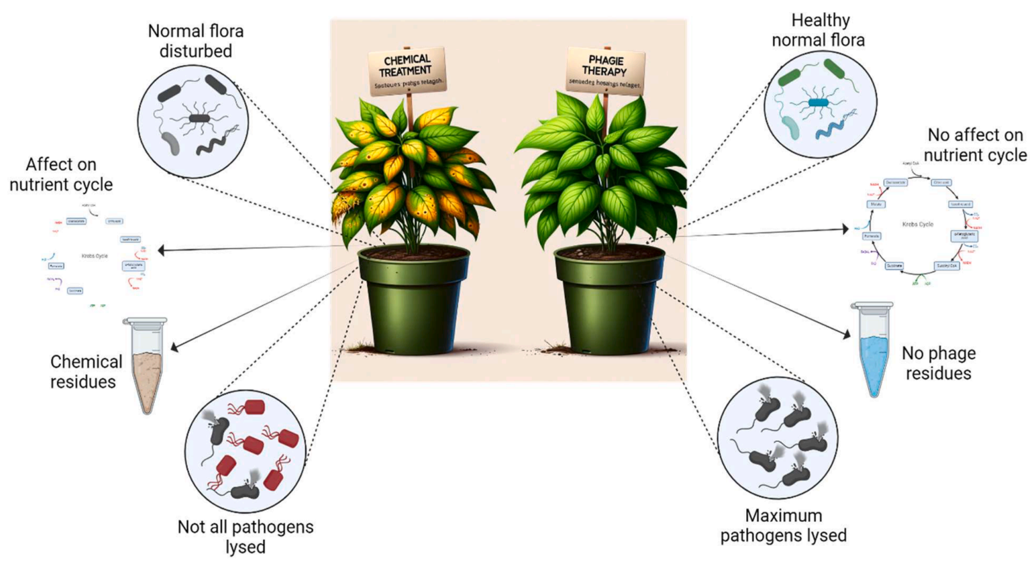

Fig. 4. The comparison of phage therapy with chemically treated diseased plants. Figure created in Biorender.

3.5. Mechanisms of action of biocontrol agents

Biocontrol agents use different mechanisms of action depending on their cellular machinery and interactions with pathogens and the production of antimicrobial compounds, such as extracellular enzymes iron sequestration, that interfere with cell wall synthesis and other cellular processes [139] (Table 2).

The most frequently reported means of action are hyper parasitism, antibiotic-interpose repression, lytic enzyme production, endolysins or homolysis, production of hydrogen cyanide, competition, and inductance of host resistance. In hyper-parasitism, biocontrol agents absorb pathogens' nutrients, slowing their metabolism and ultimately dying [144]. In mycoparasitism, one fungus attacks another fungus through an antagonistic mechanism [145]. In antibiotic-interpose repression, biocontrol agents produce microbicidal compounds that kill or inhibit the growth of pathogens [144]. Some bio-control agents have lytic enzymes to inhibit pathogens by rupturing their cell membrane and nucleus [144]. Some bacteria produce toxic compounds such as hydrogen cyanide to inhibit the growth of pathogenic bacteria [145]. Hydrogen cyanide is delivered by *florescent pseudomonas* and represses the growth of pathogenic microbes [144]. In the competition, nutrients are present in fewer amounts in the environment. In such scenarios, biocontrol agents compete for the available nutrients and consume them in the background; thus, they suppress the growth of other flora, including pathogens. Several biocontrol agents are mentioned in Table 5. Fig. 5 depicts the mechanisms of action of biocontrol agents for managing plant diseases.

4. Advantages of the biocontrol agents

Biocontrol agents are a safe and sustainable alternative to chemical pesticides and antibiotic-based approaches. They do not leave harmful residues in the environment, which can pollute soil and water sources or damage the other microbial flora [156]. Biocontrol agents are selective

Table 5
The commercially available biocontrol-based products.

Biocontrol product	Biocontrol organism	Pathogen/Disease	References
BlightBan 506	*Pseudomonas fluorescens* A506	Frost damage caused by *Erwinia amylovora*, russet-inducing bacteria	[43]
Galltrol	*Agrobacterium radiobacter* Strain 84	Crown gall disease caused by *Agrobacterium tumefaciens*	[146]
Nogall	*Agrobacterium radibacter* K1026	Crown gall disease caused by *Agrobacterium tumefaciens*	[147]
Conquer	*Pseudomonas fluorescens*	*Pseudomonas tolassii*	[148]
Trichoderma 2000	*Trichoderma harzianum*	*Rhizoctonia solani, Sclerotium rolfsii, Phytium*	[140]
Primastop	*Gliocladium catenate*	Several plant diseases	[135]
Trichodex	*Trichoderma harzianum*	*Botrytis cinerea*	[141]
Trichopel	*Trichoderma harzianum*	Fungal diseases	[71]
Fusaclean	*Fusarium exosporium*	*Fusarium oxysporium*	[64]
Aspire	*Candida Oleophila*	Botrytis spp & Penicillium spp	[149]
AQ10 Biofungicide	*Ampelomyces Quisqualis*	Powdery mildews	[150]
Rotstop	*Phlebiopsis gigantea*	*Heterobasaidium annosus*	[151]
Binab T	*Trichoderma harzianum & T. polysporum*	Fungal wilt	[71,152]
Triochoseal & Trichoject	*T.viride*	*Chondrostereum purpureum* & soil pathogens	[153]
COTTON WG	*Coniothyrium minitans*	*Sclerotinia* spp	[154]
YIELDPLUS	*Cryptococcus albidus*	*Botrytis* spp & *Penicillium* spp	[151]
T-22 & T-22HB Bio Trek, Rootshield	*Trichoderma harzianum*	*Pythium, Rhizoctonia, Fusarium, Sclerotinia*	[155]

in their action and target only the pests intended to control and minimize the risk of harming beneficial organisms such as pollinators, predators, and other non-target organisms. Additionally, no resistance is associated with using biocontrol agents [157]. Biocontrol agents can establish themselves in the field and persist over time, providing long-term control of pests and diseases [158]. Using biocontrol agents is cheaper than chemical pesticides in the long run. They require less frequent applications and have a lower risk of resistance development. It is easy to inoculate and manipulate biological agents [121]. Biocontrol agents can reduce the number of chemical pesticides used in agriculture, positively affecting human health, biodiversity, and the environment [159]. Compatible with other pest management strategies: Biocontrol agents can be integrated with different pest management strategies, such as cultural practices and biological control, to provide a more holistic and practical approach. Bio-fertilizers can be fused with biological agents to increase their efficacy and make their use easy [145]. Biocontrol agents are a sustainable approach for plant diseases as they are based on natural processes and do not rely on synthetic chemicals [160]. Biocontrol agents are often safer for human health than chemical pesticides, as they have a lower risk of toxicity and contamination. Biocontrol agents are preferred for organic agriculture and crops consumed raw [161]. Biocontrol agents maintain the biodiversity in the soil as they are target-specific and do not interrupt the other microbial flora; thus, the integrity of the ecosystem is maintained. Overall, using biocontrol agents can provide a safe, sustainable, and effective means of controlling pests and diseases in agriculture.

5. Commercialization of biocontrol agents-based products

Biocontrol agents, such as beneficial microbes, insects, and other species, are gaining popularity as potential pest control options [162]. The commercialization of biocontrol agent-based solutions provides huge opportunities to manage pest issues while minimizing environmental effects and maintaining food supply. We will discuss briefly the trends, problems, and prospects for commercializing biocontrol agent-based products. The marketplace for biocontrol agent-based solutions has been consistently growing for various reasons [163]. For instance, increasing consumer awareness and regulatory scrutiny on synthetic pesticides' environmental and health consequences have enhanced interest in more secure and sustainable pest management options [156]. Second, biotechnology and microbiological research advances have made it easier to find and create new biocontrol agents that are more effective and selective against their target pests [164]. Third, the adoption by the producers of integrated pest management (IPM) techniques, which stress the application of different pest control approaches, including biocontrol, has increased the need for bio-based solutions [165].

Several corporations and academic organizations are currently working on the development and marketing of biocontrol agent-based products. These include multinational enterprises, biotechnology

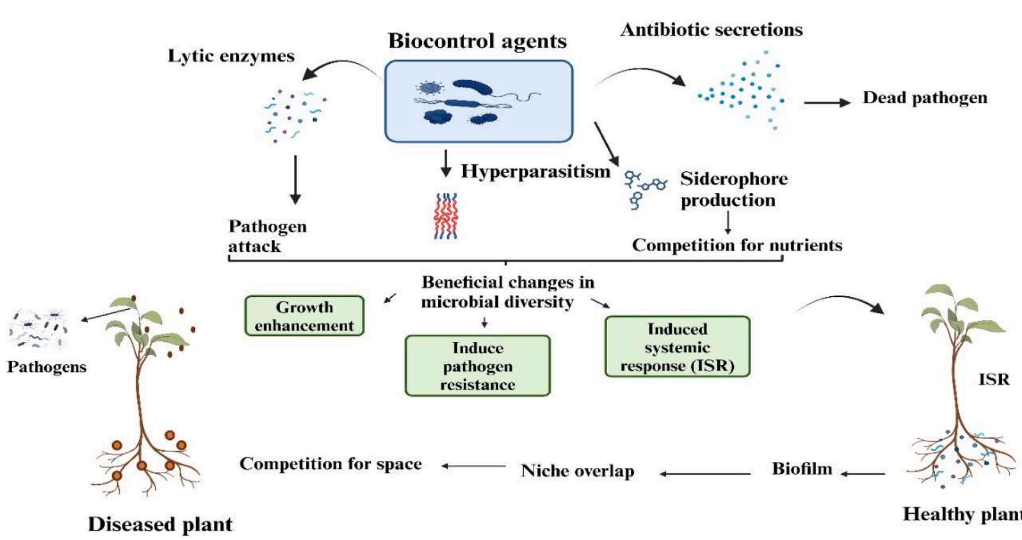

Fig. 5. Microbial biocontrol agents' mechanisms of action against plant pathogens.

entrepreneurs, university independent businesses, and public research institutions. *Bacillus thuringiensis* (Bt) is a naturally existing soil bacteria that generates insect-killing proteins harmful to specific pests such as caterpillars, beetles, and mosquitos [166]. Bt-based solutions are often used in sustainable agriculture and have been marketed for pest control in crops like maize, cotton, and vegetables [167]. Various Trichoderma species are widely recognized for inhibiting plant diseases [71]. Trichoderma-based bio fungicides treat soil-borne illnesses caused by fungi, including Fusarium, Rhizoctonia, and Pythium, in various crops [168]. Beauveria bassiana, an entomopathogenic fungus, can infect many insect pests, including aphids, whiteflies, and thrips [169]. Beauveria-based bioinsecticides have been developed to control pests in greenhouses and ornamental and field crops [170]. Ladybirds, lacewings, and predatory mites are biological control agents that reduce populations of insects such as aphids, mites, and thrips in agricultural and horticulture crops [171].

6. Challenges and prospects

Although solutions based on biocontrol agents have much promise, there are a few obstacles to their general acceptance [172]: Target pest populations, treatment techniques, and environmental factors can all affect how effective biocontrol products are. It might be necessary to optimize the composition, dose, and schedule of applications to manage pests [173] consistently. Because of the strict regulation criteria for safety, effectiveness, and evaluation of environmental impacts, the registration and authorization procedure for biocontrol products may be very time-consuming, complicated, and costly. Many biocontrol chemicals are less well accepted in the market or as protected by regulations compared to traditional pesticides [174]. Although green farming is gaining popularity, some farmers still need clarification about biocontrol agents' dependability and efficacy compared to conventional pesticides [31]. Bio-based products must be better promoted, educated, and shown to have advantages to improve market acceptability. Biocontrol agents are typically thought to be more costly than chemical pesticides [175]. For an accurate affordability analysis, however, the subsequent advantages of fewer chemical residues, environmental preservation, and effective pest management must be considered.

Commercializing goods based on biocontrol agents offers tremendous potential [31] for innovation, teamwork, and market expansion, even in the face of obstacles. Novel biocontrol agents are being discovered and old ones are being improved because of ongoing research and development activities in formulations technology, genetic engineering, and microbial biotechnology [176]. In addition to traditional agriculture, biocontrol agents are used in specialized sectors, including forestry, urban gardening, and sustainable agriculture. Increasing product demands to meet the needs of various market niches might lead to new business prospects [177]. Cooperation between government agencies, research institutions, industry players, and farmers is crucial to overcoming regulatory obstacles, sharing knowledge, and encouraging biocontrol-based integrated pest management (IPM) approaches [178]. Because biocontrol agents increase crop output while reducing adverse environmental effects, they can be essential to the sustainable intensification of agriculture [179]. Organic farming practices like agroforestry and sustainable agriculture may be used with biocontrol to create systems for food production that are durable and beneficial to the environment [180]. A viable route to long-term pest control and agricultural growth is commercializing products based on biocontrol agents. Notwithstanding obstacles like regulatory barriers, market acceptability, and performance improvement, the industry is growing due to technical developments, diversification of markets, and cooperative efforts. Organizations may capitalize on the complete potential of biocontrol agents to solve global food security concerns while protecting the environment and public health by utilizing creativity, developing collaborations, and raising awareness.

7. Conclusion

Plant diseases have significantly troubled the safety and economy of the country by affecting the central part of several economically important plants. Existing antibiotic and copper-based strategies have failed to reduce the burden of plant diseases. The Biocontrol strategy is emerging as one of the most promising approaches to controlling pathogens without causing any harm to the environment. Biocontrol has a considerable therapeutic breadth in fungal and bacterial diseases, mainly prone to existing control strategies. Less toxicity, high compatibility, specificity, easy inoculation, and eco-friendly nature are the significant and exceptional features of the biocontrol approach. However, large-scale experiments need to be conducted to assess the probability of associated risk factors affecting the activity of biological control agents to make them commercialized. Mainly, consideration should focus on allergenic properties, possibilities of harmful and toxic metabolites, rearrangement and displacement of natural strains, genetic recombination methodologies, and consequences on biodiversity, such as the impact on non-target organisms. The benefits of the biocontrol method can be exploited if we modify aspects like the formulation and use methods and integrate them with current agricultural practices. The evolutionary dynamics of the field can be seen in the potential for genetically engineered phage and advanced bio-manufacturing systems. Specific plant pathogens will be able to be targeted with high precision by custom phage designed using technologies such as CRISPR-Cas.

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CRediT authorship contribution statement

Ihtisham Ul Haq: Writing – original draft, Validation, Methodology, Conceptualization. **Kashif Rahim:** Writing – review & editing. **Galal Yahya:** Visualization. **Bushra Ijaz:** Visualization. **Sajida Maryam:** Writing – review & editing, Validation. **Najeeba Parre Paker:** Visualization, Validation.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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