

Review Article

Plant Growth-promoting Microorganisms Isolated from Plants as Potential Antimicrobial Producers: A Review

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ABSTRACT

The agricultural industry worldwide faces challenges in the struggle against plant diseases. In efforts to increase agricultural intensities, the dependency on agrochemicals for crop protection has become significantly high. Moreover, the increasing use of agrochemical-based products has resulted in multidrug-resistant pathogens and environmental pollution. This paper reviews the biocontrol capacity of plant growth-promoting microorganisms (PGPMs) originating from plants towards plant pathogens. The current trend in discovering new compounds has shown antimicrobial activity gaining immense interest due to its vast potential. On a related note, PGPMs are an aspect of that research interest that can be further explored as antimicrobial producers. In this work, the types of biocontrol mechanisms pertaining to PGPMs as well as their roles in biocontrol activity were covered. A biocontrol approach exploits disease-suppressive microorganisms to improve plant health by controlling related pathogens. The understanding of these microorganisms and

mechanisms of pathogen antagonism are primary factors in ensuring improvement for future applications. Inevitably, there is indeed room for rigorous expansion with respect to PGPMs in the future of agriculture.

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INTRODUCTION

Infections caused by microorganisms such as bacteria, fungi, and parasites are known to be significant problems for humans, animals, and plants. The discovery of penicillin in 1928 revealed that microorganisms may contribute to known existing issues, due to the abundant bioactive substances produced within their cells (L.-Q. Xu et al., 2017). Some pathogens have been shown to develop antimicrobial-resistant properties, leading to increased morbidity, mortality, and healthcare costs (Pratiwi et al., 2017).

In food and agriculture, the use of metals, heavy metals, and biocides have both direct and indirect impacts on the growth of antimicrobial resistance in bacteria that can invade the food chain (Cheng et al., 2019). As described by Horrigan et al. (2002), traditional agriculture, includes high-yielding plants, mechanised tillage, inorganic fertilisers, and chemical pesticides, which have in turn lead to problems such as biodiversity loss (Hole et al., 2005) and impacts on soil biota and related health problems (Aktar et al., 2009). In order to boost crop yields in a sustainable and environmentally responsible manner, most of these current agricultural methods that require the use of chemical fertilisers, herbicides, fungicides, and insecticides need to be re-examined (Glick, 2012).

This scenario leads to increased research focused on the development of new antibiotics and bioactive compounds in the fight against multidrug-resistant microbes (Bérdy, 2005) and biocontrol agents against plant diseases (Köhl et al.,

2019). The use of PGPMs as a biological control agent in the form of biopesticides has been considered one of the best practices for the sustainability of agroecosystems as they provide solutions to issues such as resistance to pests, conventional chemical pesticides, and public concern regarding the side effects of pesticides on the environment and eventually on human health (Mishra et al., 2015). A study by Moin et al. (2020) showed a suppression of root rotting fungi by 55.5% in 2017, and 63.6% in 2018 in sunflowers as compared to other treatments, including carbendazim, a commercial fungicide. Therefore, the use of PGPMs in the management of plant diseases has emerged as a new future alternative.

Moreover, there is an abundance of possible microorganism sources to attain biocontrol for plant growth. PGPMs, such as rhizobia, mycorrhizae, and plant growth-promoting bacteria, have been documented for decades to boost plant growth under stressed and non-stressed conditions (Naamala & Smith, 2020). According to Bérdy (2005), these would include endophytes. Prashar et al. (2013) and Rekha et al. (2010) also included rhizobacteria for this purpose. In brief, PGPMs indeed possess the capacity to serve as biocontrol agents against plant pathogens, and in addition they are effective in preserving the soil quality and increasing crop yield in a sustainable approach.

Plant Growth-Promoting Microorganisms

Plants are perceived as meta-living beings

with a particular microbiome and have advantageous interactions and associations with related microorganisms (Mendes et al., 2013). A greater understanding of the interactions of a plant with its microbiome has improved knowledge of its ability to affect its microbiome and vice versa (Jones et al., 2019). In natural settings, plants are associated with a microbial population in healthy tissues (Darma et al., 2016). PGPMs are in fact central to microbial communities. PGPMs have been associated with several types of plants and are commonly found in many environments. In general, PGPMs can be divided into two main groups: plant growth-promoting (rhizo)bacteria (PGPRs or PGPBs) and plant growth-promoting fungi (PGPFs).

A typical example of plant growth-promoting bacterium (PGPBs) is the beneficial free-living soil bacteria (Agrillo et al., 2019). PGPBs are known to potentially occupy various plant compartments, including the rhizosphere, the endosphere (inner plant tissues), and the phyllosphere (an aerial portion of plant leaves) (Zhang et al., 2019). Rhizobacteria, among a variety of other microorganisms, often populate the rhizosphere, a small area of soil directly affected by the root system. This may be due to the abundance of nutrients and energy sources produced by different plant exudates, such as amino acids and sugars, compared to the bulk soil region (Gray & Smith, 2005).

According to Cecagno et al. (2015), the genus *Azospirillum*, a known PGPR, is comprised of free-living, nitrogen-fixing

bacteria, which can colonise the root surface or the intercellular spaces of the host plant roots by adhesion. The advantages of *Azospirillum* inoculation for plants were mainly due to its ability to fix atmospheric nitrogen (Fukami et al., 2018) and the ability to secrete phytohormones such as auxins, gibberellins, cytokinins, and nitric oxide, which promote plant growth (Fibach-Paldi et al., 2011).

The definition of PGPF is equivalent to that of PGPR, according to Murali and Amruthesh (2015), except that the species are fungi (including true fungi as well as oomycetes) rather than bacteria. PGPFs have the ability to provide plants with many benefits in terms of growth and defence against pests and pathogens (Hossain et al., 2014). Larran et al. (2016) described a *Fusarium* sp. that was isolated from wheat that showed a significant reduction in spore germination of *Drechsleratritici-repentis*, which causes tan spot of wheat, to be suppressed by 52% compared to the control. Another study by Fiume and Fiume (2008) identified the inhibition of *Pyrenochaeta lycopersici*, which causes corky root in tomato, by *Trichoderma viride* 18/17 SS, which increased up to 81.2% in dual culture. In addition, the study also proved that all tomato plants treated with *T. viride* showed significant differences from untreated tomato plants with regards to corky root symptoms during growth in a greenhouse in which the McKinney index rose from 3.3 to 23.3%.

In addition, numerous endophytic microorganisms have also been classified

as PGPMs and are defined as part of the plant microbiota (Zhang et al., 2019). These microorganisms are classified as non-pathogenic bacteria or fungi that live in healthy living tissues of plants but do not inflict any damage to the plants (Bacon & White, 2000). As described by W. Xu et al. (2019), these endophytes are isolated from various plant species, and some of them may have the potential to be utilised as biocontrol agents against plant diseases such as white fruit disease which usually threatens mulberry fruit productivity. Moreover, endophytes have also been shown to stimulate the growth of mulberry seedlings. The results showed that the highest promotion potential was caused by *Bacillus* sp. CW16-5, which increased shoot length and root fresh weight by 83.37% and 217.70%, respectively (W. Xu et al., 2019).

Previous reports have shown that endophytes can aid germinating seeds and improve plant growth through several approaches such as nitrogen fixation, phosphate solubilisation, siderophore production, and bioactive enzyme release (Agrillo et al., 2019; Liotti et al., 2018; Wu et al., 2020; W. Xu et al., 2019). Furthermore, W. Xu et al. (2019) mentioned another promising source of natural biological control antagonists (BCAs). Endophytic bacteria are considered natural BCAs due to their production of possible bioactive substances. In addition, compared to soil-derived fungi or other settings, endophytic fungi have a greater affinity mostly with the host and can more easily infect and flourish in plants, thereby offering better resistance

and desirable effects on plants (Backman & Sikora, 2008).

Biocontrol Mechanism of PGPMs

Biocontrol of plant diseases can be described as suppressing plant-pathogen populations using living organisms (Heimpel & Mills, 2017). Biocontrol agents use different mechanisms to shield plants from pathogens (Köhl et al., 2019), which able to reduce the use of agrochemicals in agricultural production (Naamala & Smith, 2020). As described by Sehrawat and Sindhu (2019), many rhizobacteria produce an antagonistic effect by using diverse mechanisms of biocontrol including creating a competitive environment for nutrient uptake against the phytopathogenic microorganisms, the root colonisation ability and producing a secondary metabolite as protective agents. In addition, the rhizobacteria also help in regulating the production of virulence factor using quorum sensing and inducing a physical defence mechanism of the host such as induced systemic resistance (ISR) and systemic acquired resistance (SAR) as a mechanism of biocontrol (Sehrawat & Sindhu, 2019).

Beneduzi et al. (2012) identified PGPBs that indirectly suppress the activity of phytopathogens based on competition for living capacity (space and nutrients) or the development of antibacterial metabolites (Beneduzi et al., 2012). This metabolite is responsible for the antagonistic action of certain species against phytopathogens such as *Alternaria solani* (Attia et al., 2020), *Aspergillus flavus* (Chen et al., 2019), and

Fusarium solani (Bahroun et al., 2018). Several studies have documented the use of lytic enzymes, such as chitinases and proteases, in addition to antimicrobial peptides or proteins, polyketides, phenolic compounds, and biosurfactants (Abdalla et al., 2020; Agrillo et al., 2019; Chen et al., 2019; Wu et al., 2020; W. Xu et al., 2019; Zloch et al., 2016), in the development of antimicrobial metabolites.

PGPBs may also implement other biocontrol mechanisms to directly enhance plant development, such as biofilm production (Naik et al., 2015), nutrient uptake, nitrogen fixation (Carvalho et al., 2014), mineral phosphate solubilisation (Wang et al., 2017), phytohormones, and siderophore release (Gamalero & Glick, 2015). A study by Chen et al. (2019), also found that the endophyte *Bacillus velezensis* LDO2 produces specific metabolites such as fengycin, surfactin, bacilysin, bacillaene, and macrolactin, which constitute the basis for pathogen inhibition. Other strategies involve altering the cell membrane permeability of the pathogen, triggering cell lysis, and producing siderophores that can minimise pathogen growth by reducing iron accessibility (Zloch et al., 2016).

There is also a non-pathogenic soil *Bacillus* spp. with the ability to form endospores. *Bacillus* spp. have been found to colonise root surfaces, whereby they enhance plant growth by triggering fungal mycelia lysis (Turner & Backman, 1991). This strain is advantageous as it can withstand intense pH, temperature, and osmotic conditions (Ashwini & Srividya, 2013). *Bacillus* spp.

are also considered safe biological agents, leading to their higher potential of use, due to various actions, including antibiosis, siderophore production, cell wall degrading enzymes, and lipopeptide producers (Islam et al., 2012).

Generally, PGPMs can promote plant growth via both direct and indirect mechanisms. Direct mechanisms are characterised by employing the bacterial traits that directly promote plant growth, while indirect mechanisms refer to bacterial traits that prevent one or more plant pathogenic organisms from functioning (Olanrewaju et al., 2017). By using either one or more of these mechanisms, PGPMs can influence plant growth and development. In the remainder of this review, the mechanisms of action of biocontrol agents and identify some promising examples of these PGPMs in controlling plant disease would be discussed. Figure 1 provides application of PGPMs in biocontrol activity and their mode of action.

Antimicrobial Secondary Metabolites as Antibiosis Agents. Compant et al. (2005) described an essential mechanism in biological control as the production of antimicrobial secondary metabolites. Pathogens tend to interact with microbial biological control agents via antibiosis or hyperparasitism to assure crop yields (Köhl et al., 2019). This can be seen in the number of beneficial rhizobacteria capable of secreting antibiotics and other compounds that are antagonistic to plant pathogens. *Agrobacterium*, *Bacillus*, *Burkholderia*,

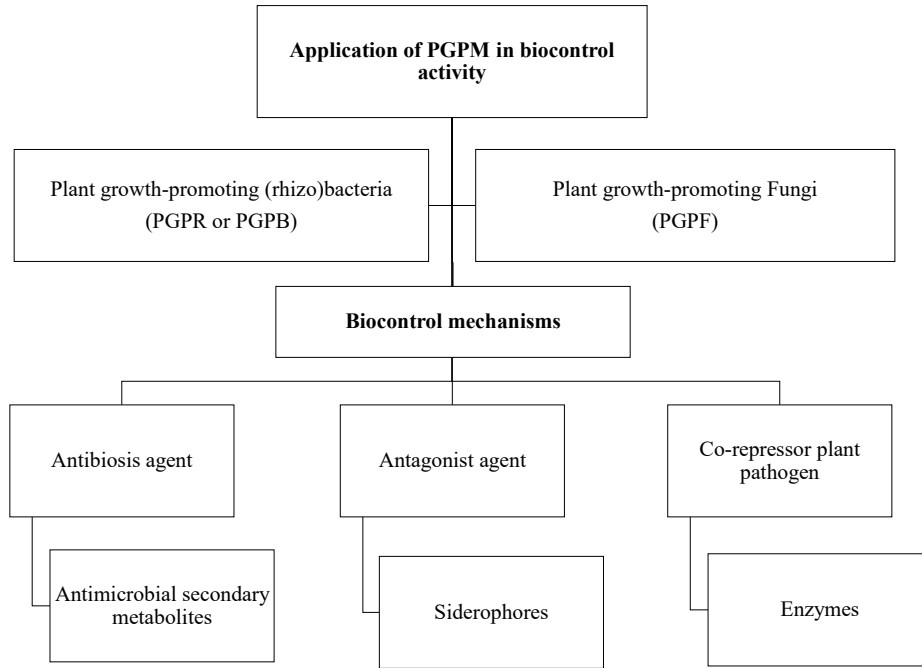


Figure 1. Application of PGPMs in biocontrol activity and their mode of action

Pseudomonas, and *Streptomyces* are effective antagonists against soil-borne pathogens (Barea et al., 2005; Montealegre et al., 2003; Prapagdee et al., 2008). These have been shown to be broad-spectrum antimicrobial producers against *Aeromonas hydrophila*, *Escherichia coli*, and *Staphylococcus aureus* (Vachee et al., 1997), *Bacillus subtilis*, *Candida albicans*, and *Proteus vulgaris* (Trujillo et al., 2007). This remarkable feature was further highlighted by Rekha et al. (2010) such that *Pseudomonas* spp. are also pertinent as root dips for biological control of soil-borne plant pathogens, seed inoculants, and antibacterial agents.

Essentially, there is a significant correlation between antimicrobial development and disease inhibition. For

instance, *Pseudomonas* spp. can yield antibiotic 2,4-diacetylphloroglucinol (2,4-DAPG), which regulates and reduces *Gaeumanomyces graminis* var. *tritici* infection in wheat as described by de Souza et al. (2003). Moreover, in the field trials by Weller (2007), a 60% suppression of pathogen infection was documented from the bacterization of wheat seed with antibiotic phenazine-1-carboxylic acid (PCA) activity by *Pseudomonas fluorescens* strains 2-79. Most *Bacillus* spp., as well as many other pathogenic fungi such as *Alternaria solani*, *Aspergillus flavus*, *Botryosphaeria ribis*, *Colletotrichum gloeosporioides*, *Fusarium oxysporum*, *Helminthosporium maydis*, and *Phomopsis gossypii* synthesise antibiotics, namely

polymyxin, circulin, and colistin, which are active against gram-positive and gram-negative bacteria (Maksimov et al., 2011). Meanwhile, Cawoy et al. (2014) reported that the metabolites secreted by the *Bacillus* genus resulted in an antagonism effect responsible for the disruption of the fungal membrane, resulting in mycelium, conidia, or zoospores for oomycete pathogens. These metabolites are extensively used as biocontrol agents for their antibacterial and antifungal properties, particularly surfactin, iturin, plipastatin, and fengycin (Harwood et al., 2018).

In addition, endophytes are also capable of producing a wide variety of biologically active secondary metabolites. For example, Vaz et al. (2009) reported endophytic fungi isolated from a tropical orchid extract have shown to demonstrate the strongest antimicrobial activities against the pathogenic yeasts and may be considered to produce bioactive natural products. J. C. Lee et al. (1995) further added that hydroxypestalopyrone, pestalocide, pestalopyrone, and pyrone are some examples of antifungal compounds produced by isolated endophytic *Pestalotiopsis microspora* from *Torreya taxifolia*. From the Sepik River region in Papua New Guinea, isolated endophytic *Pestalotiopsis jester* have been reported to produce antifungal jesterone and hydroxy-jesterone that counter multiple phytopathogenic fungi (Li & Strobel, 2001). Other work by W. Xu et al. (2019) also mentioned broad-spectrum antagonism on phytopathogens demonstrated by four strains of *Pantoea*

spp. (CA15-30, CA15-43, CA15-44, and XA15-46), one strain of *Pseudomonas* spp. (XA15-33), and 26 isolates of *Bacillus* spp. This activity can easily be associated with antibiotic biosynthesis.

Siderophore Production as Antagonist Agents. A limiting factor in iron availability for microbial growth is due to the low solubility of Fe^{3+} ions, yet it is an essential consideration for disease suppression (Köhl et al., 2019). Microorganisms capable of producing high levels of siderophores with high iron affinity may be selected for biological control against phytopathogens. By limiting the level of iron that is usable for a pathogen, siderophore-producing microbes can prevent or minimise pathogen proliferation (Shen et al., 2013), causing them to lose their ability to function as pathogens (Olanrewaju et al., 2017).

In terms of site competition, siderophores are low molecular weight ferric ion specific chelating agents that can be differentiated into three main categories, hydroxamates, catecholates, and carboxylates. As described by Pahari et al. (2017), hydroxamate type of siderophore is mostly produced by the bacteria and fungi. The catecholate siderophore, produced by the bacteria and carboxylate siderophore produced by bacteria like *Rhizobium* sp., *Staphylococcus* sp. and fungi like *Mucorales* sp. According to Battu and Reddy (2009), several strains from the *Pseudomonas fluorescens putida* group can release siderophores that are beneficial for plant growth and biocontrol. This may be due to fungal inhibition

within the rhizospheres of several crops. Furthermore, several fungi, such as *Trichoderma asperellum*, also produced iron-binding siderophores to control Fusarium wilt (Segarra et al., 2010). Ahmad et al. (2008) stipulated another noteworthy advantage, aside from acquiring iron, is that siderophore-producing endophytic bacteria can also inhibit phytopathogenic growth by depleting iron. In another study, Calvente et al. (2001) proved the growth inhibition of phytopathogenic moulds by bacterial siderophores containing spent medium and associated the antifungal activity with siderophore concentration.

Enzymes as Co-repressor of Plant Pathogens. In some cases, excretion of cell wall degrading enzymes (CWDEs) supports the biocontrol of secondary metabolites. Cell wall degradation can typically be associated with a range of chitinases, β -1,3-glucanases, and proteases. The biocontrol strains of PGPRs that secrete CWDEs have a strong inhibitory effect on the hyphal growth of fungal pathogens. Enzymes, namely, chitinase and β -1,3-glucanase, degrade chitin, which is the major component of the fungal cell wall (Labuschagne et al., 2010). Nevertheless, for hyperparasites such as oomycota, pathogen cell walls are penetrated by cellulases (Köhlet al., 2019). Xylanases, cellulases, and chitinases are some of the enzymes secreted during colonisation and infection processes. As these enzymes or their degradation products maybe directly recognised by the host, they may induce a defensive response (Druzhinina et al.,

2011). *Curtobacterium* sp. XA15-35, demonstrated antifungal activity, which counters *Sclerotinia sclerotium* (W. Xu et al., 2019). This attribute of XA15-35 is associated with significant phosphate solubilisation besides the production of several hydrolytic enzymes (chitinase and protease).

A previous study by Radjacommare et al. (2004) also documented mycelial growth inhibition of *Rhizoctonia solani* from induced resistance activity. *Pseudomonas fluorescens* apparently demonstrated an induced systemic resistance (ISR) to hinder the sheath blight pathogen by the latter, which increased the production of chitinase genes in rice. This example reflects various endophyte-derived compounds that are capable of inducing plant defence responses. However, due to the high complexity of hyperparasitism, the production of a single enzyme may not be a good competitor for biocontrol purposes. In addition, according to Karlsson et al. (2017), understanding the role of enzymes in biocontrol requires the perception of the entire cascade of events, including the signal regulation of its various secondary metabolites. The beneficial microorganisms were found to be able to incorporate ISR to enhance the protective ability of the whole plant to multiple infections (Conrath et al., 2015). For instance, the degree of stunting, leaf malformation, and wilting induced by *Xylella fastidiosa* in *Catharanthus roseus* (Lacava et al., 2007) can be abated by *Curtobacterium flaccumfaciens*.

Table 1
Biocontrol of plant pathogens by plant growth-promoting microorganism and its biocontrol mechanisms against plant pathogen

Biocontrol agent	Target pathogen	Plant/Disease	Mechanism of action	Reference
<i>Bacillus subtilis</i> SBMP4, <i>Lysinibacillus fusiformis</i> NBRC15717, <i>Achromobacter xylosoxidans</i> NBRC15126	<i>Alternaria solani</i>	Early blight disease (Tomato)	Antibiotics, secondary metabolites, and enzyme	Attia et al. (2020)
<i>Pseudomonas</i> sp. EFP-121	<i>Macrophomina phaseolina</i> <i>Fusarium</i> spp.	Root rot (Sunflower)	Siderophores, ammonia, HCN, and induced systemic resistance	Moin et al. (2020)
<i>Pseudomonas protegens</i> N	<i>Aspergillus niger</i>	Bunch rot and black mould (Tomato)	Antimicrobial peptide	Agrillo et al. (2019)
<i>Bacillus velezensis</i> LDO2	<i>Alternaria tenuissima</i> , <i>Aspergillus flavus</i> , <i>Aspergillus niger</i> , <i>Fusarium oxysporum</i> , <i>Fusarium moniliforme</i> , <i>Rhizoctonia solani</i> , <i>Rhizopus</i> sp.	Leaf blight, damping-off, crown rot, root rot, and pod rot (Peanut)	Siderophores and secondary metabolites	Chen et al. (2019)
<i>Bacillus velezensis</i> OEE1	<i>Verticillium dahliae</i>	Verticillium wilt (Olive tree)	Secondary metabolites	Azabou et al. (2020)
<i>Rahnella aquatilis</i> B16C	<i>Fusarium solani</i>	Root rot (Faba bean)	Secondary metabolite, siderophores, PRN, and HCN	Bahroun et al. (2018)
<i>Burkholderia stabilis</i> PG159	<i>Cylindrocarpum destructans</i>	Rot disease (Ginseng)	Production of antimicrobial metabolites and/or proteins	Kim et al. (2018)

Table 1 (Continued)

Biocontrol agent	Target pathogen	Plant/Disease	Mechanism of action	Reference
<i>Alcaligenes faecalis</i> S18, <i>Bacillus cereus</i> S42	<i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i>	Fusarium wilt (Tomato)	Chitinases and/or proteases	Abdallah et al. (2016)
<i>Bacillus</i> sp.	<i>Drechsleratritici-repentis</i>	Tan spot (Wheat)	-	Larran et al. (2016)
<i>Pseudomonas fluorescens</i> EB69, <i>Pseudomonas cepacia</i> EB139, <i>Pseudomonas</i> spp. ERG6	<i>Ralstonia solanacearum</i>	Bacterial wilt (Eggplant)	Antifungal/inhibitory compounds and siderophores	Ramesh and Phadke (2012)
<i>Streptomyces griseus</i>	<i>Fusarium oxysporum</i> f. sp. <i>lycopersici</i>	Wilt (Tomato)	Chitinases	Anitha and Rabeeth (2009)
<i>Streptomyces</i> spp. AtB42, <i>Bacillus subtilis</i> M51 PI	<i>Pyrenochaeta lycopersici</i>	Corky root (Tomato)	Antibiotics, antifungal metabolites, and enzyme	Fiume and Fiume (2008)
<i>Bacillus subtilis</i>	<i>Phytophthora capsica</i>	Phytophthora blight (Red pepper)	Siderophores, HCN, IAA, phosphatase, and ACC-deaminase	K. J. Lee et al. (2008)
<i>Rhizobium meliloti</i>	<i>Macrophomina phaseolina</i>	Charcoal rot (Groundnut)	Siderophores, IAA	Arora et al. (2001)
<i>Pseudomonas chlororaphis</i> PCL1391	<i>Fusarium oxysporum</i>	Foot and root rot (Tomato)	Phenazine-1-carboxamide, HCN, chitinases, and proteases	Chin-A-Woeng et al. (1998)

Table 1 (Continued)

Biocontrol agent	Target pathogen	Plant/Disease	Mechanism of action	Reference
<i>Chryseobacterium</i> sp. ISE14	Phytophthora capsica	Phytophthora blight (Pepper)	Root colonisation, biofilm formation, and phosphate solubilisation	Sang et al. (2018)
<i>Cladosporium oxysporum</i> PH30409, <i>Trichoderma koningiopsis</i> PH30441	<i>Alternaria panax</i> , <i>Fusarium oxysporum</i> , <i>Fusarium solani</i> , <i>Phoma herbarum</i> , <i>Mycocentrospora acerina</i>	Root rot (<i>Panax notoginseng</i>)	Antibiosis, competition, induction of defense response, and mycoparasitism	Zheng et al. (2017)
<i>Trichoderma hamatum</i> , <i>Bacillus</i> sp.	Drechslera tritici-repentis	Tan spot (Wheat)	-	Larran et al. (2016)
<i>Streptomyces lavendulae</i> 16R3B	Pythium aphanidermatum	Damping-off (Cucumber)	Chitinases, antibiosis, and competition	Costa et al. (2013)
<i>Trichoderma viride</i>	Pyrenochaeta lycopersici	Corky root (Tomato)	Competition and mycoparasitism antibiotics	Fiume and Fiume (2008)

Note. HCN: Hydrogen cyanide; IAA: Indole acetic acid; ACC: 1-aminocyclopropane-1-carboxylic acid; PRN: Pyrrolnitrin

Application of PGPMs in Biocontrol Activity

In the agricultural sector, microorganisms with several benefits can be valuable and are significant to the bioeconomy in order to fight plant disease. Thus, biocontrol is one of the tools used to manage plant pathogens with low environmental effects (Larran et al., 2016). PGPMs are considered a good biocontrol strategy and play important roles in plant growth-promoting (W. Xu et al., 2019). According to Agrillo et al. (2019), biocontrol agents can be obtained from the extraction and purification of specific compounds isolated from PGPMs. PGPMs have been shown to have several secondary metabolites with antimicrobial properties, resulting in significant antagonistic activity against phytopathogenic fungi (W. Xu et al., 2019). Kim et al. (2018) also indicated that biological metabolites produced from bacteria should generally be considered bio-pesticides. Table 1 shows a few studies establishing pathogen biocontrol using PGPMs and their mechanisms against plant pathogens.

Rhizospheres have been identified as plant growth and health enhancers by supporting mechanisms such as enhanced soil nutrient uptake, phytohormone production and release, and increased plant resistance to environmental stress, which have adverse effects on soil phytopathogens, including fungi, viruses, and nematodes (Prashar et al., 2013). Research done by Abro et al. (2019) also found three promising endophytic fungi, *Penicillium* sp., *Hypocrea* sp., and *Lasiodiplodia theobromae*, which

pose as biocontrol agents against wilting of cucumber crops caused by *Fusarium oxysporum* f. sp. *cucumerinum*. These three endophytes effectively reduced the severity of cucumber Fusarium wilt and enhanced cucumber growth (Abro et al., 2019). Murali and Amruthesh (2015) showed that there is a major disease protection of 62% and 58% under greenhouse and field conditions, respectively, in plants pretreated with a conidial suspension of *Penicillium oxalicum*, which is a PGPF against downy mildew disease. Previous research has also reported PGPBs such as *Pseudomonas* (Wicaksono et al., 2018), *Cellulosimicrobium*, and *Bacillus* (Zouari et al., 2016), showing potential against phytopathogenic fungi and/or insects.

CONCLUSION AND FUTURE RECOMMENDATIONS

In this study, plant growth-promoting microorganisms (PGPMs) have shown inherent potential as biocontrol agents against plant pathogens. A great deal of work has already been done in this area. Nevertheless, ongoing efforts are still needed to extend the reliability of these biocontrol products. This is important for the realisation of commercialisation in biocontrol agents because of the high quality and low costs gap between chemical and biological control tools. The complexity of microbial events and their interactions with the environment can be further understood with better screening assays and multi-omics analyses. Such information will pave the way for a generation of markers for the effectiveness

of biocontrol agents. Furthermore, the use of such techniques will allow researchers to measure the influences of plant genotypes and the inherent microbial population on the ecology of a system, apart from suggesting a systematic method to discover novel microorganisms with desired traits.

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CONFLICT OF INTEREST

Authors declare no conflict of interest in this project.

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