Australasian Plant Pathology (2024) 53:1–14
https://doi.org/10.1007/s13313-023-00959-z

REVIEW

The role of *Streptomyces* species in controlling plant diseases: a comprehensive review

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Received: 25 September 2023 / Accepted: 4 December 2023 / Published online: 12 December 2023

Abstract
Numerous factors contribute to the decline in crop yields, including plant diseases caused by bacteria, fungi, and viruses. The management of these diseases with chemical fertilizers is not a sustainable approach. This review briefly summarizes the role, mechanisms, advantages, and disadvantages of using *Streptomyces* species in plant disease management as an alternative method is needed to address the problems of using chemicals. One promising alternative is to use microbes to manage plant diseases. *Streptomyces*, a gram-positive saprophytic bacterium, is particularly effective at combating plant diseases. They produce bioactive-rich antimicrobial metabolites and enzymes that can kill or inhibit the growth of plant pathogens. *Streptomyces* species are widely distributed in nature but are especially abundant in the rhizosphere, the soil region surrounding plant roots. *Streptomyces* can be used as bioinoculants to protect plants from diseases. In addition to their disease-fighting abilities, they can promote plant growth in many ways. They produce plant growth-promoting substances, such as indole-3-acetic acid (IAA), cytokinin, and siderophores. They also suppress diseases through antibiosis, mycoparasitism, and nutrient competition. *Streptomyces* can also supply plants with essential minerals, i.e., iron, copper, phosphorus, and sulfur. Therefore, it concluded that *Streptomyces* species can be used as an alternative to chemicals to control plant diseases.

Keywords Antimicrobial compounds · Biological control · Plant Diseases · Plant growth promotion · *Streptomyces*

Introduction

The pressure to meet rising food demands propelled the adoption of chemical fertilizers and pesticides to maximize agricultural production (Bhardwaj and Agrawal 2014), and the decline in agricultural productivity can be attributed to many factors, with pests and pathogens being the most prominent. The prevalence of pathogen infections among crops can range from 20 to 40%, significantly impacting overall yields (Savary et al. 2012). The widespread application of chemical substances in agriculture can lead to a cascade of detrimental effects, including the accumulation of harmful residues in the environment, the evolution of fungicide resistance in plants, and the unintended proliferation of non-target and beneficial microbes (Bharathi et al. 2004). Developing genetically resistant crops is a lengthy process that requires innovative methods to overcome agricultural productivity limitations (Rey and Dumas 2017). Consequently, focusing on microorganisms is a viable strategy for enhancing agricultural productivity. Microbes are essential in plant disease management due to their environmental friendliness.

Plant beneficial microbes are abundant in the rhizosphere region, which is used as bio inoculants and can maintain the soil environment by fixing the nitrogen, solubilizing nutrients like phosphate and potassium, liberating plant growth stimulating constituents, synthesis of antibiotic compounds, and improvement of soil organic matter content through biodegradation processes (Bhardwaj and Agrawal 2014). Among all microbes, actinomycetes receive wide attention because of their potential antibiotic production, which is used for controlling various plant pathogens. Their mechanism includes mycoparasitism, nutrient competition, production of hydrolytic enzymes and antimicrobial metabolites, and regulation of plant defense. As per Bergey's Manual of Systematic Bacteriology (Whitman et al. 2012),

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actinomycetes are renamed actinobacteria, of which *Streptomyces* is widely studied since it can be grown in the laboratory on artificial media. *Streptomyces* sp. contributes about 10% of soil microflora with antifungal, antibacterial, antiviral, and antioxidant activities. 60% of antibiotic production is by *Streptomyces*, besides producing hormones like IAA and siderophore, which are responsible for improving plant growth. In a nutshell, using actinomycetes possessing antimicrobial activity might be an alternative for chemical fertilizers in plant disease management owing to their low cost of production, environmental safety, and reduction in natural non-replenishable resources. Considering its importance and potentiality, the application of *Streptomyces* spp. as a bioinoculant and alternative to chemical additives, besides its mechanisms in managing plant diseases and causes of diseases, is reviewed here.

Actinobacteria

Combining the characteristics of bacteria and fungus, actinobacteria are widespread in compost, atmosphere, and freshwater basins at varying depths worldwide. This gram-positive bacterium is classified under the Actinomycetes class and Actinomycetales order of the kingdom of bacteria's Actinobacteria phylum, Actinomycetes order, and Actinomycetaceae family. It possesses a high genomic G + C content of 74% by molecular weight (Elamvazhuthi and Subramanian 2013). Nonthakaew et al. (2022) and Peng et al. (2020) isolated many isolates from plant rhizosphere, including *Streptomyces* spp., and explored their potential antimicrobial activity.

Waksman and Henrici (1943) familiarized *Streptomyces* for the first time as the type genus of the family *Streptomycetaceae*, distinguished by physiological and morphological characteristics, type of fatty acids chains, phospholipids, peptidoglycan, GC content (%), chemical constituents of cell walls, 16 S rRNA analysis and DNA hybridization (Bhardwaj and Agrawal 2014).

Actinobacteria produces an array of secondary metabolites with high commercial interest, among which genus *Streptomyces* tops in the production with the discovery of actinomycin. Functions employed include degrading organic substrates like proteins, fats, and cellulose; therefore, its ability to produce microbial bioactive compounds makes actinobacteria one of the most explored microbes among prokaryotes. The secondary metabolites of actinobacteria are known for their role in various physiological, cellular, and biological processes (Selim et al. 2021).

Streptomyces is a significant genus representing over 500 species of chemoorganotrophic, filamentous Gram + ve, and non-acid-fast organisms. The majority of the species are mesophile (10–37 °C) while some are thermophile (45–55 °C) with pH of 6.5-8.0 (e.g.) *Streptomyces thermoflavus, S. thermonitrificans* and *S. thermovulgaris* (Gowdar et al. 2018). They are sensitive to water-logged conditions, form arthrospores, and are more drought-resistant. Few reports illustrated that sandy loam and calcareous soil possess more *Streptomyces* than heavy clay soil. Substrate and aerial mycelium production occur in which substrate hyphae are 0.5 – 0.1 µm diameter. As it ages, the production of aerial mycelium begins, forming a chain of spores (conidia) (Wildermuth 1970; Wildermuth and Hopwood 1970). The spores are formed by fragmentation and are arranged in helical, wavy, or straight chains. The colonies grow slowly with initial smooth edges and progress into crosswise mycelial threads that appear velvety, powdery, floccose, or granular with the typical earthy odor.

Actinomycetes distribution

Actinomycetes are widely distributed in natural ecosystem habitats such as soil, rhizosphere soil, actinmycorrhizal plants, hypersaline soil, limestone, freshwater, marine, sponges, volcanic cave—hot spot, desert, air, insects' gut, earthworm castings, goat feces, and endophytic actinomycetes. The most important features of microbial bioactive compounds are that they have specific microbial producers: their diverse bioactivities and their unique chemical structures. Actinomycetes represent a source of biologically active secondary metabolites like antibiotics, biopesticide agents, plant growth hormones, antitumor compounds, antiviral agents, pharmacological compounds, pigments, enzymes, enzyme inhibitors, anti-inflammatory compounds, single-cell protein feed, and biosurfactant (Farda et al. 2022; Selim et al. 2021). The rhizospheric streptomycetes can prevent the fungal infection of plant roots by producing antifungal drugs. Actinomycetes are also excellent sources of lytic enzymes, antibiotics, and other bioactive compounds due to their metabolic diversities (Vurukonda et al. 2018).

According to the recent study conducted by Ambikapathy et al. (2022b), the insect gut microbiota significantly contributes to the nutrition of termites, cockroaches, and aphids. *Apis mellifera*, the honeybee, has a complex digestive tract, which makes it an attractive model for studying gut bacteria. Occasionally, *Streptomyces* spp. can dominate the bee stomach. The bee guts have also been recorded to contain *Nocardiopsis* sp., which expresses an antibiotic biosynthesis gene. The *Bacillus* strains native to the bees and the actinomycetes have selectively killed two other drug-resistant Gram-positive pathogens.

The *Nocardiopsis alba* has been detected in the guts of honeybees. In earthworm casting, the actinomycetes and industrial enzymes have rarely been studied. The casting action of *Actinomyces* sp. nourishes and enriches the soil. By burrowing and eating, the earthworms redistribute the organic materials in the soil, increase the soil's permeability, improve the exchange of gases with the atmosphere, and increase microbial activity. Several medicinal applications can be recognized for casting actinomycetes in animal and human medicines (Salcedo-Porras et al. 2020). Most actinobacteria are environmental residents, as opposed to the obligate pathogens. Actinobacteria play vital roles in the life and reproduction of many insects. The streptomycetes protect the European beewolf pups against microbial pathogens infection. *Oerskovia* and *Nocardiopsis* spp. are the major bacterial species detected in goat feces, generating more antifungal agents than antibacterial ones. Antibiotics from *Streptomyces* spp., such as monensin and flavomycin, have been utilized to promote the growth rate of cattle (Selim et al. 2021). An endophyte is a microorganism that lives entirely or partially inside the plant's tissues. The longstanding relationship between the endophytic bacteria and their host plants has increased their numbers (Huang et al. 2021).

Actinomycete-derived bioactive compounds effectively control silver scurf disease in potatoes, which is caused by the fungus *Helminthosporium solani* (Gao et al. 2021). *Streptomyces* species are particularly good at producing antifungal compounds. One example is Amycolatopsis CP2808, which makes ansa carbamitocins antibiotics. Ansamitocin also has anticancer properties. Another example is Nocardia sp., an endophytic actinomycete with ansamitocin (Selim et al. 2021).

Chen et al. (2021) found that marine actinomycetes interact with various marine organisms, such as sponges, corals, echinoderms, and puffer fish. These interactions may promote the evolution of secondary metabolic pathways in marine actinomycetes, producing diverse chemical compounds. These interactions may have significant ecological and biotechnological implications. These compounds may have novel biological activities, including antimicrobial, antitumor, and antiviral ones. In addition to the interaction with the other species of marine organisms, the marine actinomycetes may thrive in both the planktonic and the biofilm habitats, and most of these actinomycetes strains have been identified in the sediments (Schmidt et al. 2019).

What factors encourage and result in actinomycetes adopting one of these life choices is unknown. In general, the planktonic and biofilm-forming bacteria have diverse species compositions. Many physicochemical characteristics, such as temperature, pH, pressure, total organic carbon, and salinity, affect the abundance of actinomycetes in ocean sediment. The optimal conditions for actinomycetes vary depending on the location. *Streptomyces*, *Micromonospora*, and *Actinomyces* strains have been discovered at depths up to 500 m (Jagannathan et al. 2021). For instance, *Micromonospora* sp. may be more abundant at 450 m than lower levels. Furthermore, several investigations have demonstrated that the actinomycetes samples taken from the coastal sediments are more heat resistant than those collected from the salt water, suggesting that the heat-resistant spore forms of the actinomycetes dominate the deposits over their vegetative states (Jagannathan et al. 2021).

Actinomycetes isolation

Isolation of the soil actinomycetes

Actinomycetes can be isolated from soil samples using several general bacterial isolation procedures, such as serial dilution, pouring plates, streaking, and centrifugation (Majhi 2021). Centrifugation followed by repeated dilutions can improve the growth of actinomycetes in soil samples. However, none of these techniques can specifically isolate actinomycetes, making it difficult to purify them (Shivabai and Gutte 2019).

A pure culture of non-actinomycete bacterium can inhibit the growth of actinomycetes. Therefore, six methods have been developed for selective isolation of the soil actinomycetes mainly (i) nutritional selection, in which the media contain nutritional components that the actinomycetes preferentially consume; (ii) selective inhibition, in which the growth inhibitors such as antifungal drugs and antibiotics are included to prevent growth of the non-actinomycete bacteria, (iii) physical or chemical sample pretreatments; to limit the non-actinomycete bacteria, (iv) enrichment approaches; where the nutritional medium can be supplemented with extra nutrients, which favor growth of the actinomycetes, and\ or inhibit the growth of the other microorganisms, (v) the membrane filter method, which does not require pretreatment, specific medium, and\or antibiotics; and (vi) the integrated method that can use combinations of various procedures (Kumar and Jadeja 2016). Pretreatment of the soil can either increase the growth of actinomycetes or remove most of the unwanted Gram-negative bacteria. Several pretreatment methods have been developed for the different actinomycetes taxonomy. Under natural settings, the streptomycetes play a significant role in the actinomycetes population. As a result, physical pretreatment can facilitate the isolation of the streptomycetes. In contrast, chemical pretreatment and\ or a combination of physical and chemical pretreatments may reduce the isolation of the other bacteria (Ezeobiora et al. 2022).

Isolation of the marine actinomycetes

The phylum Actinobacteria adapts to and colonizes many hostile habitats, including the deep sea; its metabolic capability, morphology, and metabolism are incredibly varied. Generally, the growth conditions of unusual marine actinomycetes differ from terrestrial actinomycetes (Subramani and Sipkema 2019). A considerable proportion of the bacteria in under\ unexplored habitats are viable but not culturable since only around 1% of these bacteria can form colonies on the isolation media using the standard techniques. For this reason, high-throughput molecular methods, such as metagenomics, are becoming increasingly popular for studying microbial communities in environments where culture-based approaches are largely ineffective (El-Tarabily et al. 2009; Gutleben et al. 2018). Furthermore, culture-independent studies on the functional features of actinomycetes have improved methods for growing and cultivating the previously uncultivable actinobacteria (Kumar and Jadeja 2016).

The actinomycetes' taxonomy, physiology, and environmental parameters, including pH, culture temperature, oxygen, and nutritional requirements, must be understood and controlled to isolate the undiscovered or uncommon actinomycetes (El-Tarabily 2003; Subramani and Sipkema 2019). The growth media should usually have osmotic values similar to seawater since sodium (Na^+) is a critical medium for developing marine microorganisms such as *Salinispora* spp. Furthermore, different carbon sources (i.e., soluble starch, glucose, dextrose, maltose, trehalose, mannitol, raffinose, fucose, chitin, glycerol, and oatmeal), and combined carbon-nitrogen sources (i.e., peptone; yeast extract, casein, malt extract, meat extract, beef extract, and tryptone) should be added to the isolation media. Furthermore, sediment extracts, sponge extracts, and genuine saltwater should be introduced alone or as supplements to simulate the natural growth conditions of marine life (El-Tarabily et al. 1996; Subramani and Sipkema 2019).

Before isolating the uncommon actinomycetes, marine materials, mainly sediments, may be added to eliminate the common terrestrial actinomycetes and undesirable microorganisms. Isolation of the rare Actinomycetes from the marine samples is commonly done by diluting and mixing the samples with sterile natural and\ or artificial seawater, deionized dist (El-Tarabily 2006; Siro et al. 2022). Water with NaCl, multi-salts, vitamin B mixtures, Ringer's solution, and\ or saline solution. The marine actinomycetes have been preferentially isolated using a variety of pretreatment procedures; most commonly, the environmental sample is to be dried within a laminar airflow cabinet and then diluted with seawater or saline before it is heated (Siro et al. 2022). Due to their resistance to desiccation and heat, the actinomycetes spores can be used to select against the other Gram-positive bacteria.

The actinomycetes spores resist various substances, including benzethonium chloride, chlorhexidine gluconate, phenol, sodium dodecyl sulfate, and several antibiotics. Selective separation of the actinomycete taxa has been achieved using these substances (Hayakawa 2008). These substances kill or inhibit the aerobic Gram-negative bacteria, endospore-forming bacteria, and pseudomonads within 30 min., thus increasing the possibility of selective isolation of the actinomycetes while reducing the other forms of bacteria. Moreover, the ultrasonic waves can disperse the actinobacterial propagules from the soil particles, thereby increasing the actinobacterial strains and lowering those of undesirable bacteria (Rasuk et al. 2017).

Streptomyces as a bio inoculant

Streptomyces spp. may decompose biopolymers such as lignocellulose, starch, and chitin in soil, water, and organic debris (Fig. 1). *Streptomyces* as a bioactive chemical became apparent following the discovery of streptomycin, which paved the door for detecting antimicrobial substances. Malviya et al. (2009) and Gopalakrishnan et al. (2011) isolated many actinomycetes from rhizosphere soil from diverse sites. They screened them for their new microbial chemicals. *Streptomyces* sp. alone accounted for 75% of the antibiotics used in agrochemicals and medicines among actinobacteria (Berdy 2005). Through the synthesis of extracellular hydrolytic enzymes, they have also gained significance in plant disease control (Joo 2005; Prapagdee et al. 2008). The formation of thread-like filaments in the soil is helpful for the effective colonization of the rhizosphere (Al Raish et al. 2021; Elnahal et al. 2022). In addition, they encourage plant development, make nutrients accessible, and combat infections. They are administered as spore suspension, culture filtrate, wettable granules, wettable powder, and emulsifiable concentrates for synthesizing antibiotics, bactericides, insecticides, fungicides, acaricides, and herbicides (Chouyia et al. 2022).

The mechanism employed by *Streptomyces* against plant pathogens

Streptomyces species can inhibit infections by providing bioactive chemicals, extracellular enzymes, and antibiotics (Fig. 2). Table (1): summarizes the effectiveness of *Streptomyces* isolates and its secondary metabolites in managing plant pathogens.

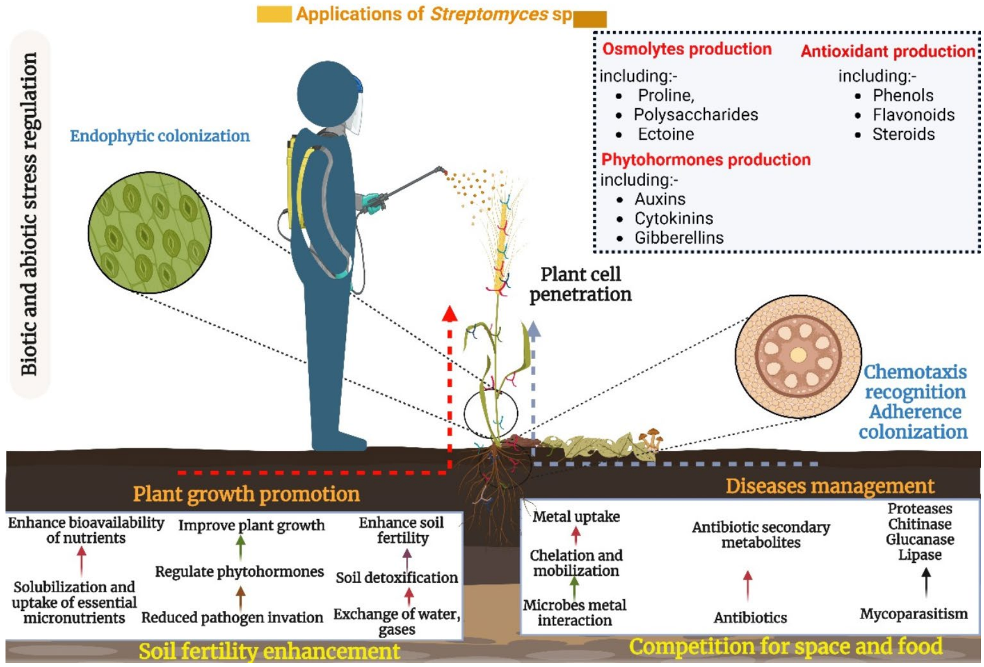

Fig. 1 Applying *Streptomyces* to plants (via spray or soil inoculation) can improve their uptake of metals, production of hydrolytic enzymes, phytohormones, osmolytes, and antioxidants

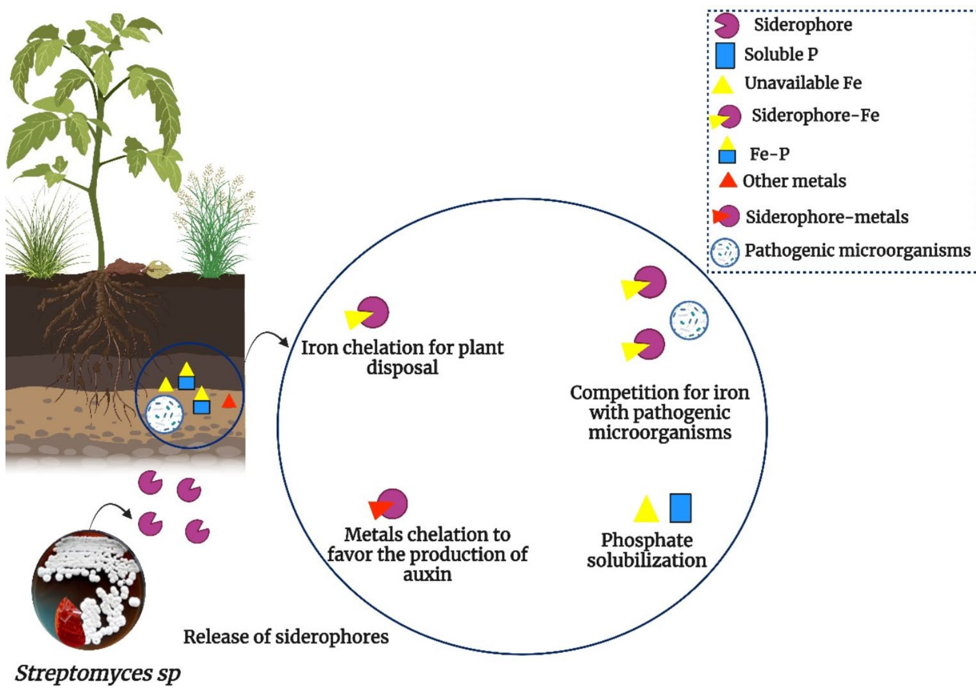

Fig. 2 Mechanism of *Streptomyces* in control plant pathogens

Mycoparasitism / hydrolytic enzymes

Like parasitism and antibiosis, enzymes play a crucial role in the biocontrol of plant diseases. Antifungal activity needs cell wall disintegrating enzymes such as 1,3-glucanase, chitinase, cellulase, and protease (Haggag and Mohamed 2007). Actinobacteria are potential makers of -1, 3-glucanase, chitinase, amylase, pectinase, cellulase, xylanase, lipase, and protease and are isolated from agricultural soil actinomycetes (Sonia et al. 2011). The complete dissolution of *Sclerotium rolfsii, Sclerotinia minor, Aspergillus*, and *Fusarium oxysporum* was caused by glucanase and chitinase (Hassan et al. 2011; El-Saadony et al. 2022).

Two hundred and eighty-three chitinolytic actinomycetes were isolated from rhizosphere soils of Sisaket Province and Ubon Ratchathani, Thailand was separated by Pattanapipitpaisal and Kamlandharn (2012), among which 13 isolates showed potentiality for inhibiting the fungal growth emphasizing its usage as a biocontrol agent. Srividya et al. (2012) reported β-1, 3 and β-1, 4 glucanases, chitinase, protease

Table 1 The effectiveness of *Streptomyces* isolates and its secondary metabolites in managing plant pathogens

Plant	Disease	Pathogen	*Streptomyces*	Active compounds	Reference
Lemon	Sour rot	*Geotrichum candidum*	*Streptomyces* sp. RO3	Oligomycins A	(Goudjal et al. 2014)
Turfgrass	Crown disease	*Rhizoctonia solani*	*S. violaceusniger* YCED9	Natamycin; 4-Phenyl-3-butenoic acid	(Gao et al. 2021)
Porphyra	Red rot	*Pythium porphyrae*	*Streptomyces* sp. AP77	Rapamycin	(Zhang et al. 2016)
Chilli	Root rot, blight	*Alternaria brassiceae, C. gloeosporioides*	*Streptomyces* spp.	4-Phenyl-3-butenoic acid	(Srividya et al. 2012)
Sweet pea	Powdery mildew	*Oidium* sp.	*Streptomyces* sp.	Natamycin	(Sangmanee et al. 2009)
Ginger	Rhizome rot	*F. oxysporum* f. sp. *zingiberi*	*Streptomyces* spp.	Antimycin A17	(Manasa et al. 2013)
Tomato	Damping-off	*R. solani*	*Streptomyces* spp.	Oligomycins A and C	(Goudjal et al. 2014)
		Rhizoctonia solani	*Streptomyces* sp. S30	Rapamycin	(Gao et al. 2021)
	Fusarium wilt	*Fusarium oxysporum* f.sp. *lycopersici*	*S. rochei* ACTA 1551	Pyrroles (Pyrroles [1,2- a] pyrazine-1,4-dione	(Kanini et al. 2013)
	Root rot	*R. solani*	*Streptomyces vinaceusdrappus* S5MW2	1 H-Pyrrole-2- carboxylic acid (PCA)	(Yandigeri et al. 2015)
		R. solani	*S. toxytricini* vh6	Propanoic acid	(Patil et al. 2011)
Pepper	Blight	*Phytophthora capsici*	*Streptomyces* spp. 47W08, 47W10	Avermectins	(Yandigeri 2021)
		Colletotrichum gloeosporioides	*S. cavurensis* NRRL 2740	Lucensomycin	(Intra et al. 2011)
Chickpea	Fusarium wilt	*Fusarium* spp.	*Streptomyces* (CAI-24, CAI-121, CAI-127, KAI-32 and KAI90)	Natamycin	(Gopalakrishnan and Ganeshkumar 2013)
	Basal rot	*Macrophomina phaseolina*	*Streptomyces sp. RO3*	Oligomycins A and C	(Goudjal et al. 2014)
Cucumber	Damping-off	*Pythium* spp.	*S. griseoviridis*	4-Phenyl-3-butenoic acid	(Junaid et al. 2013)
Onion	Bacterial rot	*Erwinia carotovora*	*S. lavendulae HHFA1*	Natamycin	(Gopalakrishnan and Ganeshkumar 2013)
Wheat	Root rot	*Fusarium cloumorum*	*S. aurantiogriseus* VSMGT1014	Oligomycins A and C	(Harikrishnan et al. 2014)
Rice	Blast	*Bipolaris oryzae, Curvularia oryzae, Fusarium oxysporum, Pyricularia oryzae, Rhizoctonia solani and Rhizoctonia oryzae- sativae*	*S. hundungensis* strain MBRL 251; Streptomyces sp. KH-614	Antimycin A17	(Nimaichand et al. 2013)
	sheath blight	*R. solani*	*S. aurantiogriseus* VSMGT1014	Oligomycins A and C	(Harikrishnan et al. 2014)
	brown spot	*Helminthosporium oryzae, R. solani*	*S. misionensis* NBRC	Rapamycin	(Poomthongdee et al. 2015)
	brown spot	*Pyricularia* sp.	*Streptomyces* strain PC 12, *Streptomyces* strain D 4.1, *Streptomyces* strain D 4.3 and *Streptomyces* strain W1	Pyrroles (Pyrroles [1,2- a] pyrazine-1,4-dione	(Chaiharn et al. 2020)
Groundnut	Stem rot	*Sclerotium rolfsii*	*Streptomyces* sp. CBE	1 H-Pyrrole-2- carboxylic acid (PCA)	(Adhilakshmi et al. 2014)
Pepper and cherry tomato	Anthracnose	*Colletotrichum gloeosporioides*	*Streptomyces sp. A1022*	Lucensomycin	(Gao et al. 2021)
Lettuce	Basal drop	*Sclerotinia minor*	*S. viridodiasticus*	Natamycin; 4-Phenyl-3-butenoic acid	(Gao et al. 2021)
	Damping off	*Pythium ultimum; Rhizoctonia solani*	*Streptomyces sp. YCED9*	Natamycin	(Chen et al. 2018)
Apple		*Botryosphaeria dothedia*	*Streptomyces rochei* A1	Propanoic acid	(Zhang et al. 2016)
Strawberries		*B. cinerea*	*Streptomyces* sp. *3–10*	Avermectins	(Lyu et al. 2017)

Table 1 (continued)

Plant	Disease	Pathogen	*Streptomyces*	Active compounds	Reference
Banana		*C. musae, C. gloeosporioides*	*Streptomyces spectabilis* NBRC 13,424	Lucensomycin	(Chen et al. 2018)
	wilt	*Fusarium oxysporum*	*S. violaceusniger G10*	Propanoic acid	(Chaiharn et al. 2020)
Red chili	Anthracnose	*Colletotrichum gloeosporioides*	*S. ambofaciens S2*	Avermectins	(Lyu et al. 2017)
Soybean	Blight	Xanthomonas campestris pv. glycines	*Streptomyces sp.*	Antimycin A17	(Chaiharn et al. 2020)
Many	Root rot, botrytis blight	*Alternaria alternata*, *Botrytis cinerea*	*S. spororaveus RDS28*	PCA	(Yandigeri et al. 2015)
	Leaf blight	*Coriolus versicolor; Phanerochaete chrysosporium*	*S. violaceusniger XL-2*		(Chaiharn et al. 2020)
	Wood rot	*Sclerotium rolfsii*	*S. hygroscopicus*	Antimycin A17	

and lipase-producing isolates from Solanaceae rhizosphere having possible role against fungal pathogens like *Alternaria alternata*, *A. brassicola*, *A. brassicaceae*, *Rhizoctonia solani, Colletotrichum gloeosporioides*, and *Phytophthora capsici*. The second most abundant organic compound in the cell wall next to cellulose is chitin, and the chitinase enzyme produced by *Streptomyces* spp. can depolymerize it. Hence, it could be exploited as a promising tool in biocontrol either directly or indirectly by using purified proteins (Sonia et al. 2011). Chitinase-producing chili rhizosphere isolates exhibited antimicrobial potential against *Colletotrichum capsici* and *Fusarium oxysporum* (Ashokvardhan et al. 2014). *S. griseoloalbus* from cucumber rhizosphere suppressed the damping-off pathogen *Pythium aphanidermatum* when compared with metalaxyl by producing cell wall degrading enzymes (El-Tarabily and Sivasithamparam 2006). The conidial germination of cucumber wilt pathogen *F. oxysporum* f. sp. *cucumerinum* was inhibited by the actinobacteria *S. bikiniensis* strain HD-087, which triggered defense-related enzyme β-1,3, glucanase, phenylalanine ammonialyase and peroxidase against the pathogen (Zhao et al. 2012).

Antibiosis

Actinobacteria are capable of producing several volatile compounds, poisons, and antibiotics. *Streptomyces* are potential makers of numerous secondary metabolites that can function as fungicides against plant diseases and ensure environmental safety among actinomycetes (Siupka et al. 2021). *S. padanus* Strain JAU4234, which generated fungichromin, actinomycin X2, and antifungalmycin 702, exhibited antifungal activity in *Rhizoctonia solani* via altering the structure of cell membranes and the cytoskeleton in addition to interacting with cellular organelles (Xiong et al. 2013). Similarly, *S. olivaceiscleroticus* AZ-SH514 and *S. antibioticus* AZ-Z710 were known to produce mycangimycin and 4-phenyl-1-napthyl-phenyl acetamide with antibacterial and antifungal activity against *Staphylococcus aureus, Micrococcus lutea, Bacillus subtilis, B. pumilus, Klebsiella pneumonia, Escherichia* (Atta 2015). Similarly, the antibiotic compounds geldanamycin, guanidylfungin A, and nigericin produced by *S. violaceusniger* YCED9 showed antifungal activity against *Phytophthora, Pythium* and *Fusarium* spp, besides making the chitinases and β-1,3-glucanase enzymes (El-Tarabily et al. 1997; Trejo-Estrada et al. 1998).

Polyoxins B and D were obtained from *S. cacaoivar* function by inhibiting the chitin syntheses (Isono et al. 1967). Mildiomycin from *Streptoverticillium rimofaciens* inhibits protein biosynthesis in powdery mildew (Harada and Kishi 1978). Polyene from *Streptomyces plumbeus* effective against *Botrytis cinerea* (El-Tarabily et al. 2010; Han et al. 2020), macrolide antibiotic oligomycin A from *S. libani* was active against pathogenic fungi *Botrytis cinerea*, *Cladosporium cucumerinum*, *Colletotrichum lagenarium*, *Magnaporthe grisea* and *Phytophthora capsici* ((Kim and Xiao 2011), and isochainin from an *S. marokkonensis* AP1 strain inhibitory towards *F. oxysporum* f. sp. *albedinis* and *V. dahliae* (Bouizgarne et al. 2009; Saxena 2014). Kasugamycin, a bactericidal and fungicidal metabolite from *Streptomyces kasugaensis, is* effective against rice blast *Pyricularia oryzae* by inhibiting the protein biosynthesis in microorganisms (Law et al. 2017) and *Pseudomonas* diseases of several crops (Sharma et al. 2014). Cyclic lipopeptide daptomycin from *S. roseosporus* (Liu et al. 2013), geldanamycin, nigericin, and Oligomycin A of *S. diastatochromogenes* exhibited inhibitory activity against many pathogenic fungi (Yang et al. 2010). The antibiotics 2,5-Piperazinedione and Pyrrolo [1,2-a] pyrazine-1,4-dione, hexahydro functions by reducing or scavenging the volume of free radicals (Morales-Gonzalez et al. 2018) exhibiting antioxidant activity.

It has been reported that actinomycetes spores can be present in the air. Moreover, it has been suggested that airborne actinomycetes, such as *Nocardia* spp., have antibacterial activity (Seratnahaei et al. 2022). Several unique bioactive microbial compounds have been produced by symbiotic and transitory bacteria in the insect digestive tracts, which include streptanoate; alpiniamide A, the alteramides A and B, coproporphyrin III, deferoxamine, demethylenenocardamine, dihydropicromycin, nocardamine, picromycin, surugamides A, B, C, D, and E, tirandamycins A and B, and valinomycin (Ambikapathy et al. 2022a; Li et al. 2022).

Volatile organic compounds (VOCs)

Propyl ester of octadecanoic acid produced by *S. albolongus* S9 was highly inhibitory to *Corynespora cassiicola*, causing spot disease in tomatoes (Devi and Rao 2017). Volatile organic compounds are diffusible and low molecular weight compounds produced by many *Streptomyces* spp. and exhibit potent antifungal activity. Aldehydes, alkanes, aromatic hydrocarbons, alcohols, alkenes, ketones, furans, esters, and ethers were created. *S. platensis* strain F-1 volatiles conferred resistance to *Rhizoctonia solani* on rice, *Sclerotinia sclerotiorum* on oilseed rape, and Botrytis cinerea on strawberries (Wan et al. 2008). Phenol,2-methyl-5-(1-methylethyl) (Carvacrol) from *Streptomyces griseus* has a cytotoxic effect on peroxidant activity, antifungal activity against *Penicillium glabrum*, *P. capisci*, *R. solani*, *F. moniiliforme*, *S. sclerotiorum*, and *Cladosporium herbarum* (Danaei et al. 2014). Cyclohexanol, benzaldehyde, and naphthalene possessed antimicrobial effects (Danaei et al. 2014). VOCs secreted by *S. alboflavus* TD-1 include activity against *Aspergillus ochraceus* (Yang et al. 2018). Inhibition of *Sclerotinia sclerotiorum* mycelial growth and spore germination was achieved by the VOCs Cyclohexanol, decanol, 2-ethyl-1-hexanol, nonanol, benzothiazole, and dimethyl trisulfide (Fernando et al. 2005; Al Hamad et al. 2021; Alwahshi et al. 2022).

Bacterial pathogens

S. termitum ATC-2 developed the antibacterial chemical aloesaponarin II, which is effective against the rice bacterial blight disease (Donghua et al. 2013). Similarly, Mingma et al. (2014) reported that *Streptomyces* sp. strain RM 365 inhibited *Xanthomonas campestris* pv. glycines, which causes bacterial pustule on soybean, and *Streptomyces* sp. strain OE7 inhibited *Pectobacterium carotovorum* and *P. atrosepticum*, which causes soft rot of potatoes, by up to 90% (Baz et al. 2012).

Root colonizer and defense activator

The rhizosphere is a reservoir for all chemical and biological interactions in the soil matrix, and it contains a variety of helpful and hazardous bacterial species. (Glick 2012; Raaijmakers et al. 2009). One of the fundamental characteristics of biocontrol agents is their ability to colonize the roots efficiently, with more colonization resulting in greater efficiency against plant infections. Unlike pathogenic microorganisms, helpful microorganisms mobilize plant nutrients and guard against plant illnesses (Solanki et al. 2013).

A superior model of actinomycetes for rhizosphere colonization is *S. griseoviridis* isolated from sphagnum peat (Tahvonen 1982) used against cucumber root rot, damping-off in crucifers and carnation fusarial wilt. Cheng et al. (2019) reported the colonization of *Sclerotinia sclerotiorum* in oilseed rape by *S. felleus* YJ1and enhanced activities of Peroxidase (PO), polyphenol oxidase (PPO), superoxide dismutase (SOD) associated with plant disease resistance (Kim and Hwang 2007). POD aids in lignin formation by enhancing the thickness of the cell wall, PPO oxidizes phenols to quinone, and phenylalanine ammonia-lyase (PAL) strengthens the production of phenolic compounds lignans and phytoalexin which promotes systemic resistance in the plant (Wang et al. 2013).

Plant growth promotion

Like other PGPRs, *Streptomyces* can stimulate plant growth and enhance crop output by obtaining nutrients or secreting growth regulators (Fig. 2). The inoculation of *Streptomyces* strains into plants such as tomato, wheat, Sorghum, and rice increased plant biomass (Palaniyandi et al. 2011). Several pathways enhanced plant growth, including phosphate solubilization, N_2 fixing, ACC deaminase synthesis, sulfur oxidation, and iron acquisition (Nassar et al. 2003; Jaemsaeng et al. 2018). Tomato plants infected with the endophytic *Streptomyces* sp. GMKU 336 strain that produces 1-aminocyclopropane-1-carboxylate deaminase (ACCD) was waterlogged resistant (Jaemsaeng et al. 2018). Five *Streptomyces* isolates, i.e., *S. tsusimaensis, S. caviscabies, S. setonii*, and *S. africanus*, were significantly efficient against chickpea wilt induced by *F. oxysporum* and *F. ciceri* besides improving plant development ability on Sorghum and rice crops (Gopalakrishnan and Ganeshkumar 2013).

Phosphate solubilization

Phosphorus is necessary for plant growth, but its availability in soil is limited and must be supplemented with artificial fertilizers (Fig. 2). Due to its quick immobilization, most are leached out, and little is accessible for the plants (Shigaki et al. 2006). Being a potential root colonizer and an agent for transforming insoluble phosphorus into available (Hamdali et al. 2008) through the production of solubilizing acids such as propionic acid, lactic acid, citric acid, gluconic acid, malic acid, succinic acid, and oxalic acid, the filamentous

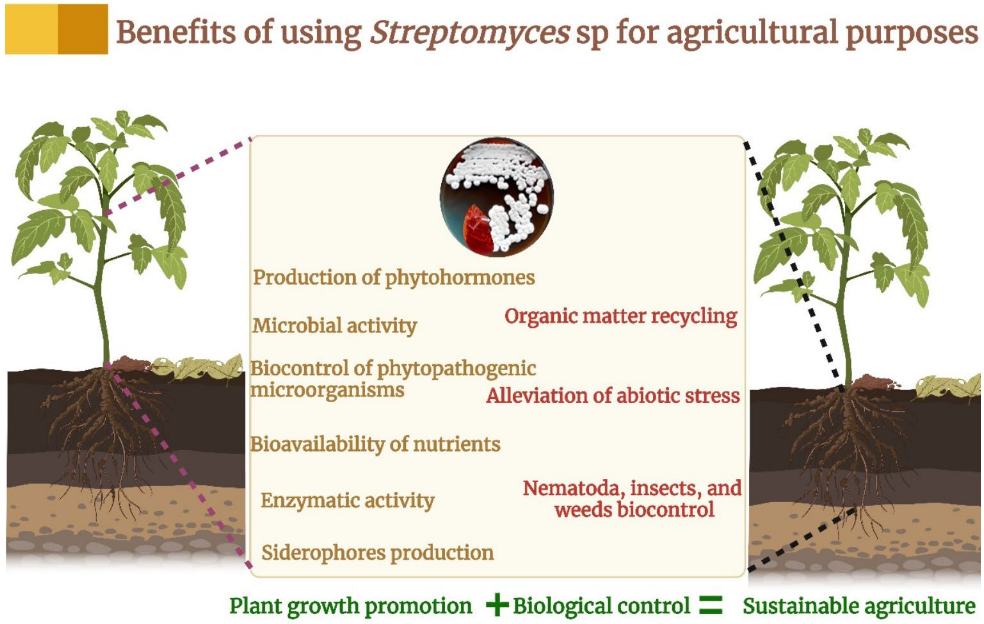

Fig. 3 Advantages of using *Streptomyces* in agriculture

Streptomycetes sp. are given due consideration; consequently, *S. griseus* and other *Streptomyces* (Jog et al. 2014).

Siderophore production

The siderophore-producing rhizobacteria prevent the proliferation of pathogenic microorganisms mainly belonging to *Streptomyces Serratia Pseudomonas Rhizobium* and *Bradyrhizobium* genera (Fig. 2)(Kuffner et al. 2008). *Streptomyces* spp., produces hydroxymate-type siderophore that protects the plants against pathogens (Khamna et al. 2009). *Streptomyces rochei* IDWR 19 produces a hydroxamate siderophore at 34.17 mg/l (Jog et al. 2014).

IAA production

The synthesis of growth regulators also stimulates plant development. Principal auxin is IAA, which performs several tasks, including cell differentiation, elongation, division, embryonic and fruit development, vascular tissue differentiation, organogenesis, root patterning, apical hook creation, and apical dominance (Khamna et al. 2009). *Streptomyces* species from the tomato rhizosphere, such as *S. rochei, S. rimosus*, and *S. olivaceoviridis*, can create IAA and promote plant development through higher seed germination (Fig. 2), root elongation, and root dry weight (El-Tarabily 2008). It has been discovered that *Streptomyces* produces natural auxin (IAA) (El-Tarabily 2008; Khamna et al. 2009). Gibberellins and cytokinin-like substances produced by *S. rimosus, S. olivaceoviridis*, and *S. rochei have* also been reported to stimulate plant development (Palaniyandi et al. 2011). Auxins also aid in promoting root hairs, lateral root development, and sugar production, all of which play a crucial part in microorganisms' early colonization of roots. *Streptomyces* sp., which generates IAA and siderophore, enhances the availability of trace elements such as zinc and iron and promotes root development and elongation (Çakmakçi et al. 2006).

Commercially available strains

Ten *Streptomyces* species have been registered as commercial products (Vurukonda et al. 2018), and a few others are in the early phases of formulation development for commercial use. Mycostop and Actinovate, two actinobacterial compositions, have been commercially exploited for decades. Due to the presence of the antifungal antibiotic aromatic heptaenepolyene, Mycostop (*S. griseoviridis* K61 strain isolated from sphagnum peat) is authorized for treatment against seed and soil-borne fungal infections in Canada, the European Union, and the United States. Additionally, to stimulate plant development, the Actinovate produced from the *S. lydicus* WYEC 108 strain inhibits the growth of *Pythium ultimum* and *Rhizoctonia solani*. Additionally, Actinovate has been utilized to prevent *Fusarium*, *Phytophthora*, *Verticillium*, and foliar diseases, including powdery and downy mildew (Vurukonda et al. 2018). Blasticidin-S against rice blast and Kasugamycin against Phytophthora-led root rot and leaf spot in diverse crops have been registered in the United States and Ukraine, respectively (Aggarwal et al. 2016). The wettable *Streptomyces* sp. Di-944 formulation reduces *Rhizoctonia solani*-caused damping off disease in tomatoes (Sabaratnam and Traquair 2002).

Advantages and disadvantages of *Streptomyces* bio-inoculant

Actinomycete metabolites are naturally occurring and are growing in relevance in plant disease control. Due to its prevalence, dominance, and promise as an agrochemical, it might be economically marketed (Solanki et al. 2013). Less hazardous and environmentally benign; Targets the specific organism and decomposes rapidly; Provides micronutrients and balances the soil nutrient cycle; Regulates the plant's metabolism to protect it from illness. Effective colonizer of roots and promoter of mycorrhizal colonization. Storage is a significant issue; the Failure rate is low. The growth rate is sluggish compared to other bacterial inoculants (Fig. 3).

Conclusion and future perspectives

Due to its potential and diverse mechanisms, *Streptomyces* sp. might be utilized as a bio-inoculant for disease control. The limitation is that all strains that perform well under in vitro conditions cannot function similarly under in vivo conditions. Therefore, a practical approach must be created to identify the strain that thrives under both environments. In general, microorganisms play a vital role in plant disease control. Researchers have concentrated on *Streptomyces*, whose metabolites are employed in commercial goods, signifying its usage as a bio-inoculant for disease management. Only active *Streptomyces* species have been identified from rhizosphere soil yet. The research should focus on discovering unique, uncommon *Streptomyces* sp. from undiscovered habitats with enormous antibiotic production potential. Research should be conducted on elution techniques to commercialize the discovered antibacterial chemicals. In addition, the optimization of a suitable carrier, the avoidance of harmful metabolites, and the genetic engineering of a successful strain will aid in producing agricultural products for commercial use.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s13313-023-00959-z.

Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to this article.

References

Adhilakshmi M, Latha P, Paranidharan V, Balachandar D, Ganesamurthy K, Velazhahan R (2014) Biological control of stem rot of groundnut (*Arachis hypogaea* L.) caused by *Sclerotium Rolfsii* Sacc. With actinomycetes. Arch Phytopathol Plant Prot 47(3):298–311. https://doi.org/10.1080/03235408.2013.809224

Aggarwal N, Thind SK, Sharma S (2016) Role of secondary metabolites of actinomycetes in Crop Protection. In: Subramaniam G, Arumugam S, Rajendran V (eds) Plant Growth promoting Actinobacteria. Springer, Singapore, pp 99–121. DOI: https://doi.org/10.1007/978-981-10-0707-1

Al Hamad BM, AlRaish SM, Ramadan GA, Alameri SSA, Al Senaani SS, AbuQamar SF, El-Tarabily KA (2021) Effectiveness of augmentative biological control of *Streptomyces griseorubens* UAE2 depends on 1-Aminocyclopropane-1-carboxylic acid deaminase activity against *Neoscytalidium Dimidiatum*. J Fungi 7:885. https://doi.org/10.3390/jof7110885

Al Raish SM, Saeed EE, Alyafei DM, El-Tarabily KA, AbuQamar SF (2021) Evaluation of Streptomycete Actinobacterial isolates as biocontrol agents against royal poinciana stem canker Disease caused by the fungal pathogen *Neoscytalidium Dimidiatum*. Biol Control 164:104783. https://doi.org/10.1016/j.biocontrol.2021.104783

Alwahshi KJ, Purayil GP, Saeed EE, Abufarajallah HA, Aldhaheri SJ, AbuQamar SF, El-Tarabily KA (2022) The 1-aminocyclopropane-1-carboxylic acid deaminase-producing *Streptomyces violaceoruber* UAE1 can provide protection from sudden decline syndrome on date palm. Front Plant Sci 13:904166. https://doi.org/10.3389/fpls.2022.904166

Ambikapathy V, Babu S, Anbukumaran A, Shijila Rani A, Prakash PJMA (2022a) Isolation of actinobacteria from mangrove plants. In: Dharumadurai D (ed) Methods in actinobacteriology. Springer protocols handbooks. Humana, New York, NY. https://doi.org/10.1007/978-1-0716-1728-1_13

Ambikapathy V, Shijila Rani A, Anbukumaran A, Shanmugapriya R, Babu S (2022b) Solation of Actinobacteria from Earthworm cast. In: Dharumadurai D (ed) Methods in actinobacteriology. Springer protocols handbooks. Humana, New York, NY. https://doi.org/10.1007/978-1-0716-1728-1_8

Ashokvardhan T, Rajithasri A, Prathyusha P, Satyaprasad K (2014) Actinomycetes from *Capsicum annuum* L. Rhizosphere soil have the biocontrol potential against pathogenic fungi. Int J Curr Microbiol Appl Sci 3(4):894–903

Atta HM (2015) Biochemical studies on antibiotic production from *Streptomyces* sp.: taxonomy, fermentation, isolation and biological properties. J Saudi Chem Soc 19(1):12–22. https://doi.org/10.1016/j.jscs.2011.12.011

Baz M, Lahbabi D, Samri S, Val F, Hamelin G, Madore I, Bouarab K, Beaulieu C, Ennaji MM, Barakate M (2012) Control of potato soft rot caused by *Pectobacterium carotovorum* and *Pectobacterium atrosepticum* by Moroccan actinobacteria isolates. World J Microbiol Biotechnol 28:303–311. https://doi.org/10.1007/s11274-011-0820-5

Berdy J (2005) Bioactive microbial metabolites. J Antibiot 58(1):1–26. https://doi.org/10.1038/ja.2005.1

Bharathi R, Vivekananthan R, Harish S, Ramanathan A, Samiyappan R (2004) Rhizobacteria-based bio-formulations for the management of fruit rot Infection in chillies. Crop Prot 23(9):835–843. https://doi.org/10.1016/j.cropro.2004.01.007

Bhardwaj A, Agrawal P (2014) A review fungal endophytes: as a store house of bioactive compound. World J Pharm Pharm Sci 3(9):228–237

Bouizgarne B, Lanoot B, Loqman S et al (2009) *Streptomyces marokkonensis* sp. nov., isolated from rhizosphere soil of *Argania Spinosa* L. Int J Syst Evol Microbiol 59(11):2857–2863. https://doi.org/10.1099/ijs.0.011387-0

Çakmakçi R, Dönmez F, Aydın A, Şahin F (2006) Growth promotion of plants by plant growth-promoting rhizobacteria under greenhouse and two different field soil conditions. Soil Biol Biochem 38(6):1482–1487. https://doi.org/10.1016/j.soilbio.2005.09.019

Chaiharn M, Theantana T, Pathom-Aree W (2020) Evaluation of biocontrol activities of *Streptomyces* spp. against rice blast Disease fungi. Pathogens 9(2):126. https://doi.org/10.3390/pathogens9020126

Chen Y, Zhou D, Qi D, Gao Z, Xie J, Luo Y (2018) Growth promotion and Disease suppression ability of a *Streptomyces* sp. CB-75 from banana rhizosphere soil. Front Microbiol 8:2704. https://doi.org/10.3389/fmicb.2017.02704

Chen J, Xu L, Zhou Y, Han B (2021) Natural products from actinomycetes associated with marine organisms. Mar Drugs 19(11):629. https://doi.org/10.3390/md19110629

Cheng Q, Hu C, Jia W et al (2019) Selenium reduces the pathogenicity of *Sclerotinia sclerotiorum* by inhibiting sclerotial formation and germination. Ecotoxicol Environ Saf 183:109503. https://doi.org/10.1016/j.ecoenv.2019.109503

Chouyia FE, Ventorino V, Pepe O (2022) Diversity, mechanisms and beneficial features of phosphate-solubilizing *Streptomyces* in sustainable agriculture: a review. Front Plant Sci 13:1035358. https://doi.org/10.3389/fpls.2022.1035358

Danaei M, Baghizadeh A, Pourseyedi S, Amini J, Yaghoobi MM (2014) Biological control of plant fungal Diseases using volatile substances of *Streptomyces griseus*. Eur J Exp Biol 4(1):334–339

Devi SS, Rao KB (2017) Exploration of antimicrobial compounds from *Streptomyces* S9 against a phytopathogen, *Corynespora Cassiicola*. & Curtis) J Biopestic 10(1):1–9. https://doi.org/10.57182/jbiopestic.10.2.1-9. Berk

Donghua J, Qinying L, Yiming S, Hao J (2013) Antimicrobial compound from a novel *Streptomyces termitum* strain ATC-2 against *Xanthomonas oryzae* Pv. *Oryzae*. Res J Biotechnol 8(7):66–70

El-Saadony MT, Saad AM, Soliman MS, Salem HM, Ahmed AI, Mahmood M, El-Tahan AM, Ebrahim AAM, Abd El-Mageed TA, Negm SH, Selim S, Babalghith AO, Elrys AS, El-Tarabily KA, AbuQamar SF (2022) Plant growth-promoting microorganisms as biocontrol agents of plant Diseases: mechanisms, challenges, and future perspectives. Front Plant Sci 13:923880. https://doi.org/10.3389/fpls.2022.923880

El-Tarabily KA (2003) An endophytic chitinase-producing isolate of *Actinoplanes missouriensis*, with potential for biological control of root rot of lupin caused by *Plectosporium tabacinum*. Aust J Bot 51:257–266. https://doi.org/10.1071/BT02107

El-Tarabily KA (2006) Rhizosphere-competent isolates of Streptomycete and non-streptomycete actinomycetes capable of producing cell-wall degrading enzymes to control *Pythium aphanidermatum* damping-off Disease of cucumber. Canad J Bot 84:211–222. https://doi.org/10.1139/b05-153

El-Tarabily KA (2008) Promotion of tomato (*Lycopersicon esculentum* Mill.) Plant growth by rhizosphere competent 1-aminocyclopropane-1-carboxylic acid deaminase-producing Streptomycete actinomycetes. Plant soil 308:161–174. https://doi.org/10.1007/s11104-008-9616-2

El-Tarabily KA, Sivasithamparam K (2006) Non-streptomycete actinomycetes as biocontrol agents of soil-borne fungal plant pathogens and as plant growth promoters. Soil Biol Biochem 38(7):1505–1520. https://doi.org/10.1016/j.soilbio.2005.12.017

El-Tarabily KA, Sykes ML, Kurtböke DI, Hardy GE, St J, Barbosa AM, Dekker RFH (1996) Synergistic effects of a cellulase-producing *Micromonospora carbonacea* and an antibiotic-producing *Streptomyces violascens* on the suppression of *Phytophthora cinnamomi* root-rot of *Banksia Grandis*. Canad J Bot 74:618–624. https://doi.org/10.1139/b96-078

El-Tarabily KA, Hardy GE, St J, Sivasithamparam K, Hussein AM, Kurtböke DI (1997) The potential for the biological control of cavity spot Disease of carrots caused by *Pythium coloratum* by Streptomycete and non-streptomycete actinomycetes in Western Australia. New Phytol 137:495–507. https://doi.org/10.1046/j.1469-8137.1997.00856.x

El-Tarabily KA, Nassar AH, Hardy GE, St J, Sivasithamparam K (2009) Plant growth promotion and biological control of *Pythium aphanidermatum*, a pathogen of cucumber, by endophytic actinomycetes. J Appl Microbiol 106:13–26. https://doi.org/10.1111/j.1365-2672.2008.03926.x

El-Tarabily KA, Hardy GE, St J, Sivasithamparam K (2010) Performance of three endophytic actinomycetes in relation to plant growth promotion and biological control of *Pythium aphanidermatum*, a pathogen of cucumber under commercial field production conditions in the United Arab Emirates. Eur J Plant Pathol 128:527–539. https://doi.org/10.1007/s10658-010-9689-7

Elamvazhuthi P, Subramanian M (2013) Antagonistic activity of actinomycetes from Jeypore paddy soils against selective phytopathogenic fungi. J Mod Biol 2(3):66–72

Elnahal ASM, El-Saadony MT, Saad AM, Desoky EM, El-Tahan AM, Rady MM, AbuQamar SF, El-Tarabily KA (2022) The use of microbial inoculants for biological control, plant growth promotion, and sustainable agriculture: a review. Eur J Plant Pathol 162:759–792. https://doi.org/10.1007/s10658-021-02393-7

Ezeobiora CE, Igbokwe NH, Amin DH, Enwuru NV, Okpalanwa CF, Mendie UE (2022) Uncovering the biodiversity and biosynthetic potentials of rare actinomycetes. Future J Pharm Sci 8(1):1–19

Farda B, Djebaili R, Vaccarelli I, Del Gallo M, Pellegrini MJM (2022) Actinomycetes from caves: an overview of their diversity, biotechnological properties, and insights for their use in soil environments. 10(2):453. https://doi.org/10.3390/microorganisms10020453

Fernando WD, Ramarathnam R, Krishnamoorthy AS, Savchuk SC (2005) Identification and use of potential bacterial organic antifungal volatiles in biocontrol. Soil Biol Biochem 37(5):955–964. https://doi.org/10.1016/j.soilbio.2004.10.021

Gao Y, Ning Q, Yang Y et al (2021) Endophytic *Streptomyces hygroscopicus* OsiSh-2-mediated balancing between growth and disease resistance in host rice. mbio 12(4):10. https://doi.org/10.1128/mBio.01566-21

Glick BR (2012) Plant growth-promoting bacteria: mechanisms and applications. Scientifica 2012:1–15. https://doi.org/10.6064/2012/963401

Gopalakrishnan S, Ganeshkumar P (2013) Systematic reviews and meta-analysis: understanding the best evidence in primary healthcare. J Fam Med Prim Care Rev 2(1):9–14. https://doi.org/10.4103/2249-4863.109934

Gopalakrishnan S, Pande S, Sharma M, Humayun P, Kiran BK, Sandeep D, Rupela O (2011) Evaluation of actinomycete isolates obtained from herbal vermicompost for the biological control of *Fusarium* wilt of chickpea. Crop Prot 30(8):1070–1078. https://doi.org/10.1016/j.cropro.2011.03.006

Goudjal Y, Toumatia O, Yekkour A, Sabaou N, Mathieu F, Zitouni A (2014) Biocontrol of *Rhizoctonia solani* damping-off and promotion of tomato plant growth by endophytic actinomycetes isolated from native plants of Algerian Sahara. Microbiol Res 169(1):59–65. https://doi.org/10.1016/j.micres.2013.06.014

Gowdar S, Deepa H, Amaresh Y (2018) A brief review on biocontrol potential and PGPR traits of *Streptomyces* sp. for the management of plant Diseases. J Pharmacogn Phytochem 7(5):03–07

Gutleben J, Chaib De Mares M, Van Elsas JD, Smidt H, Overmann J, Sipkema D (2018) The multi-omics promise in context: from sequence to microbial isolate. Crit Rev Microbiol 44(2):212–229. https://doi.org/10.1080/1040841X.2017.1332003

Haggag WM, Mohamed H (2007) Biotechnological aspects of microorganisms used in plant biological control. Am Eurasian J Sust Agric Agric 1(1):7–12. https://doi.org/10.4172/scientificreports.277

Hamdali H, Hafidi M, Virolle MJ, Ouhdouch Y (2008) Rock phosphate-solubilizing actinomycetes: screening for plant growth-promoting activities. World J Microbiol Biotechnol 24:2565–2575. https://doi.org/10.1007/s11274-008-9817-0

Han JW, Kim DY, Lee YJ et al (2020) Transcription factor PdeR is involved in fungal development, metabolic change, and pathogenesis of gray mold *Botrytis Cinerea*. J Agric Food Chem 68(34):9171–9179. https://doi.org/10.1021/acs.jafc.0c02420

Harada S, Kishi T (1978) Isolation and characterization of mildiomycin, a new nucleoside antibiotic. J Antibiot 31(6):519–524. https://doi.org/10.7164/antibiotics.31.519

Harikrishnan H, Shanmugaiah V, Balasubramanian N (2014) Optimization for production of Indole acetic acid (IAA) by plant growth promoting *Streptomyces* Sp VSMGT1014 isolated from rice rhizosphere. Int J Curr Microbiol Appl Sci 3(8):158–171

Hassan A, El-Barawy A, El Mokhtar MN (2011) Evaluation of biological compounds of *Streptomyces* species for control of some fungal Diseases. J Am Sci 7(4):752–760

Hayakawa M (2008) Studies on the isolation and distribution of rare actinomycetes in soil. Actinomycetologica 22(1):12–19. https://doi.org/10.3209/saj.SAJ220103

Huang X, Ren J, Li P, Feng S, Dong P, Ren M (2021) Potential of microbial endophytes to enhance the resistance to postharvest Diseases of fruit and vegetables. J Sci Food Agri 101(5):1744–1757. https://doi.org/10.1002/jsfa.10829

Intra B, Mungsuntisuk I, Nihira T, Igarashi Y, Panbangred W (2011) Identification of actinomycetes from plant rhizospheric soils with inhibitory activity against *Colletotrichum* spp., the causative agent of anthracnose Disease. BMC Res Notes 4(1):1–9 •. https://doi.org/10.1186/1756-0500-4-98

Isono K, Nagatsu J, Kobinata K, Sasaki K, Suzuki S (1967) Studies on polyoxins, antifungal antibiotics: Part V. isolation and characterization of polyoxins C, D, E. F G H and I Agric Biol Chem 31(2):190–199. https://doi.org/10.1080/00021369.1967.10858788

Jaemsaeng R, Jantasuriyarat C, Thamchaipenet A (2018) Molecular interaction of 1-aminocyclopropane-1-carboxylate deaminase (ACCD)-producing endophytic *Streptomyces* sp. GMKU 336 towards salt-stress resistance of *Oryza sativa* L. Cv. KDML105. Sci Rep 8(1):1950. https://doi.org/10.1038/s41598-018-19799-9

Jagannathan SV, Manemann EM, Rowe SE, Callender MC, Soto W (2021) Marine actinomycetes, new sources of biotechnological products. Mar Drugs 19(7):365. https://doi.org/10.3390/md19070365

Jog R, Pandya M, Nareshkumar G, Rajkumar S (2014) Mechanism of phosphate solubilization and antifungal activity of *Streptomyces* spp. isolated from wheat roots and rhizosphere and their application in improving plant growth. Microbiology 160(4):778–788. https://doi.org/10.1099/mic.0.074146-0

Joo G-J (2005) Production of an anti-fungal substance for biological control of *Phytophthora capsici* causing phytophthora blight in red-peppers by *Streptomyces halstedii*. Biotechnol Lett 27:201–205. https://doi.org/10.1007/s10529-004-7879-0

Junaid JM, Dar NA, Bhat TA, Bhat AH, Bhat MA (2013) Commercial biocontrol agents and their mechanism of action in the management of plant pathogens. Int J Modern Plant Animal Sci 1(2):39–57

Kanini GS, Katsifas EA, Savvides AL, Karagouni AD (2013) *Streptomyces rochei* ACTA1551, an indigenous Greek isolate studied as a potential biocontrol agent against *Fusarium oxysporum* f. sp. *lycopersici*. BioMed Res Inte 2013:1–10. https://doi.org/10.1155/2013/387230

Khamna S, Yokota A, Peberdy JF, Lumyong S (2009) Antifungal activity of *Streptomyces* spp. isolated from rhizosphere of Thai medicinal plants. Int J Integr Biol 6(3):143–147

Kim BS, Hwang BK (2007) Microbial fungicides in the control of plant Diseases. J Phytopathol 155(11–12):641–653. https://doi.org/10.1111/j.1439-0434.2007.01314.x

Kim YK, Xiao C (2011) Stability and fitness of pyraclostrobin-and boscalid-resistant phenotypes in field isolates of *Botrytis Cinerea* from apple. Phytopathology 101(11):1385–1391. https://doi.org/10.1094/PHYTO-04-11-0123

Kuffner M, Puschenreiter M, Wieshammer G, Gorfer M, Sessitsch A (2008) Rhizosphere bacteria affect growth and metal uptake of heavy metal accumulating willows. Plant Soil 304:35–44. https://doi.org/10.1007/s11104-007-9517-9

Kumar RR, Jadeja VJ (2016) Isolation of actinomycetes: a complete approach. Int J Curr Microbiol App Sci 5(5):606–618

Law JW-F, Ser H-L, Khan TM et al (2017) The potential of *Streptomyces* as Biocontrol agents against the rice blast fungus, *Magnaporthe oryzae* (*Pyricularia Oryzae*). Front Microbiol 8:3. https://doi.org/10.3389/fmicb.2017.00003

Li G, Zheng X, Zhu Y, Long Y, Xia XJEM (2022) *Bacillus symbiont* drives alterations in intestinal microbiota and circulating metabolites of lepidopteran host. Environ Microbiol 24(9):4049–4064. https://doi.org/10.1111/1462-2920.15934

Liu Y, Shi J, Feng Y, Yang X, Li X, Shen Q (2013) Tobacco bacterial wilt can be biologically controlled by the application of antagonistic strains in combination with organic fertilizer. Biol Fertil Soils 49:447–464. https://doi.org/10.1007/s00374-012-0740-z

Lyu A, Liu H, Che H et al (2017) Reveromycins a and B from *Streptomyces* sp. 3–10: antifungal activity against plant pathogenic fungi in vitro and in a strawberry food model system. Front Microbiol 8:550. https://doi.org/10.3389/fmicb.2017.00550

Majhi S (2021) Applications of Yamaguchi method to esterification and macrolactonization in total synthesis of bioactive natural products. ChemistrySelect 6(17):4178–4206. https://doi.org/10.1002/slct.202100206

Malviya MK, Pandey A, Trivedi P, Gupta G, Kumar B (2009) Chitinolytic activity of cold tolerant antagonistic species of *Streptomyces* isolated from glacial sites of Indian Himalaya. Curr Microbiol 59:502–508. https://doi.org/10.1007/s00284-009-9466-z

Manasa M, Kambar Y, Pallavi S, Vivek M, Onkarappa R, TR PK (2013) Biocontrol potential of *Streptomyces* species against *Fusarium oxysporum* f. sp. *zingiberi* (causal agent of rhizome rot of ginger). J Adv Sci Res 4(04):1–3

Mingma R, Pathom-aree W, Trakulnaleamsai S, Thamchaipenet A, Duangmal K (2014) Isolation of rhizospheric and roots endophytic actinomycetes from Leguminosae plant and their activities to inhibit soybean pathogen, *Xanthomonas campestris* Pv. glycine. World J Microbiol Biotechnol 30:271–280. https://doi.org/10.1007/s11274-013-1451-9

Morales-Gonzalez M, Martinez BS, Ramirez-Rodriguez L, Gómez J, Diaz L (2018) Optimization of L-asparaginase activity of actinobacteria isolated from Guaviare river sediments in Colombia. Trop J Pharm Res 17(11):2199–2206. https://doi.org/10.4314/tjpr.v17i11.13

Nassar AH, El-Tarabily KA, Sivasithamparam K (2003) Growth promotion of bean (*Phaseolus vulgaris* L.) by a polyamine-producing isolate of *Streptomyces griseoluteus*. Plant Growth Regul 40:97–106. https://doi.org/10.1023/A:1024233303526

Nimaichand S, Tamrihao K, Yang L-L, Zhu WY, Zhang YG, Li L, Li WJ (2013) *Streptomyces hundungensis* sp. nov., a novel actinomycete with antifungal activity and plant growth promoting traits. J Antibiot 66(4):205–209. https://doi.org/10.1038/ja.2012.119

Nonthakaew N, Panbangred W, Songnuan W, Intra B (2022) Plant growth-promoting properties of *Streptomyces* spp. isolates and their impact on mung bean plantlets' rhizosphere microbiome. Front Microbiol 13:967415. https://doi.org/10.3389/fmicb.2022.967415

Palaniyandi S, Yang S, Cheng J, Meng L, Suh JW (2011) Biological control of anthracnose (*Colletotrichum gloeosporioides*) in yam by *Streptomyces* sp. MJM5763. J Appl Microbiol 111(2):443–455. https://doi.org/10.1111/j.1365-2672.2011.05048.x

Patil HJ, Srivastava AK, Singh DP, Chaudhari BL, Arora DK (2011) Actinomycetes mediated biochemical responses in tomato

(*Solanum lycopersicum*) enhances bioprotection against *Rhizoctonia solani*. Crop Prot 30(10):1269–1273. https://doi.org/10.1016/j.cropro.2011.04.008

Pattanapipitpaisal P, Kamlandharn R (2012) Screening of chitinolytic actinomycetes for biological control of *Sclerotium rolfsii* stem rot Disease of Chilli. Songklanakarin J Sci Technol 34(4):387–393

Peng F, Zhang M-Y, Hou S-Y, Chen J, Wu Y-Y, Zhang Y-X (2020) Insights into *Streptomyces* spp. isolated from the rhizospheric soil of *Panax notoginseng*: isolation, antimicrobial activity and biosynthetic potential for polyketides and non-ribosomal peptides. BMC Microbiol 20(1):1–16. https://doi.org/10.1186/s12866-020-01832-5

Poomthongdee N, Duangmal K, Pathom-aree W (2015) Acidophilic actinomycetes from rhizosphere soil: diversity and properties beneficial to plants. J Antibiot 68(2):106–114. https://doi.org/10.1038/ja.2014.117

Prapagdee B, Kuekulvong C, Mongkolsuk S (2008) Antifungal potential of extracellular metabolites produced by *Streptomyces hygroscopicus* against phytopathogenic fungi. Int J Biol Sci 4(5):330. https://doi.org/10.7150/ijbs.4.330

Raaijmakers JM, Paulitz TC, Steinberg C, Alabouvette C, Moënne-Loccoz Y (2009) The rhizosphere: a playground and battlefield for soilborne pathogens and beneficial microorganisms. Plant Soil 321:341–361. https://doi.org/10.1007/s11104-008-9568-6

Rasuk MC, Ferrer GM, Kurth D, Portero LR, Farías ME, Albarracín VH (2017) UV-Resistant actinobacteria from high-altitude andean lakes: isolation, characterization and antagonistic activities. Photochem Photobiol 93(3):865–880. https://doi.org/10.1111/php.12759

Rey T, Dumas B (2017) Plenty is no Plague: *Streptomyces symbiosis* with crops. Trends Plant Sci 22(1):30–37. https://doi.org/10.1016/j.tplants.2016.10.008

Sabaratnam S, Traquair JA (2002) Formulation of a *Streptomyces* Biocontrol agent for the suppression of *Rhizoctonia* damping-off in tomato transplants. Biol Control 23(3):245–253. https://doi.org/10.1006/bcon.2001.1014

Salcedo-Porras N, Umaña-Diaz C, de Oliveira Barbosa Bitencourt R, Lowenberger C (2020) The role of bacterial symbionts in triatomines: an evolutionary perspective. Microorganisms 8(9):1438. https://doi.org/10.3390/microorganisms8091438

Sangmanee P, Bhromsiri A, Akarapisan A (2009) The potential of endophytic actinomycetes,(*Streptomyces* sp.) for the biocontrol of powdery mildew Disease in sweet pea (*Pisum sativum*). As J Food Ag-Ind 93:e8

Savary S, Ficke A, Aubertot J-N, Hollier C (2012) Crop losses due to Diseases and their implications for global food production losses and food security. Food Secur 4(4):519–537. https://doi.org/10.1007/s12571-012-0200-5

Saxena S (2014) Microbial metabolites for development of ecofriendly agrochemicals. Allelopathy J 33(1):1–24

Schmidt R, Ulanova D, Wick LY, Bode HB, Garbeva P (2019) Microbe-driven chemical ecology: past, present and future. ISME J 13(11):2656–2663. https://doi.org/10.1038/s41396-019-0469-x

Selim MSM, Abdelhamid SA, Mohamed SS (2021) Secondary metabolites and biodiversity of actinomycetes. J Genet Eng Biotechnol 19(1):72. https://doi.org/10.1186/s43141-021-00156-9

Seratnahaei M, Eshraghi SS, Pakzad P, Ramazani AZ, Yaseri M (2022) Antimicrobial activities of the secondary metabolite extracted from a *Nocardia* strain. J Adv Biomed Sci 12(2):203–214. https://doi.org/10.18502/jabs.v12i2.9886

Sharma D, Mayilraj S, Manhas RK (2014) *Streptomyces amritsarensis* sp. nov., exhibiting broad-spectrum antimicrobial activity. Antonie Leeuwenhoek 105:943–949. https://doi.org/10.1007/s10482-014-0151-2

Shigaki T, Rees I, Nakhleh L, Hirschi K (2006) Identification of three distinct phylogenetic groups of CAX cation/proton antiporters. J Mol Evol 63:815–825. https://doi.org/10.1007/s00239-006-0048-4

Shivabai C, Gutte S (2019) Isolation of actinomycetes from soil sample using different pretreatment methods and its comparative study. Int J Res Anal Rev 6(2):697–702

Siro G, Pipite A, Christi K, Srinivasan S, Subramani R (2022) Marine actinomycetes associated with stony corals: a potential hotspot for specialized metabolites. Microorganisms 10(7):1349. https://doi.org/10.3390/microorganisms10071349

Siupka P, Hansen FT, Schier A, Rocco S, Sørensen T, Piotrowska-Seget Z (2021) Antifungal activity and biosynthetic potential of new *Streptomyces* sp. MW-W600-10 strain isolated from coal mine water. Int J Mol Sci 22(14):7441. https://doi.org/10.3390/ijms22147441

Solanki SK, Krivova NA, Haigh JD (2013) Solar irradiance variability and climate. Annu Rev Astron Astrophys 51:311–351. https://doi.org/10.1146/annurev-astro-082812-141007

Sonia M-T, Hafedh B, Abdennaceur H, Ali G (2011) Studies on the ecology of actinomycetes in an agricultural soil amended with organic residues: II. Assessment of enzymatic activities of Actinomycetales isolates. World J Microbiol Biotechnol 27:2251–2259. https://doi.org/10.1007/s11274-011-0688-4

Srividya S, Thapa A, Bhat DV, Golmei K, Dey N (2012) *Streptomyces* sp. 9p as effective biocontrol against Chilli soilborne fungal phytopathogens. Eur J Exp Biol 2(1):163–173

Subramani R, Sipkema D (2019) Marine rare actinomycetes: a promising source of structurally diverse and unique novel natural products. Mar Drugs 17(5):249. https://doi.org/10.3390/md17050249

Tahvonen R (1982) The suppressiveness of Finnish light coloured *Sphagnum peat*. Agric Food Sci 54(5):345–356. https://doi.org/10.23986/afsci.72115

Trejo-Estrada S, Paszczynski A, Crawford D (1998) Antibiotics and enzymes produced by the biocontrol agent *Streptomyces violaceusniger* YCED-9. J Ind Microbiol Biotechnol 21(1–2):81–90. https://doi.org/10.1038/sj.jim.2900549

Vurukonda SSKP, Giovanardi D, Stefani E (2018) Plant growth promoting and biocontrol activity of *Streptomyces* spp. as endophytes. Int J Mol Sci 19(4):952. https://doi.org/10.3390/ijms19040952

Waksman SA, Henrici AT (1943) The nomenclature and classification of the actinomycetes. J Bacteriol 46(4):337–341. https://doi.org/10.1128/jb.46.4.337-341.1943

Wan M, Li G, Zhang J, Jiang D, Huang H-C (2008) Effect of volatile substances of *Streptomyces platensis* F-1 on control of plant fungal Diseases. Biol Control 46(3):552–559. https://doi.org/10.1016/j.biocontrol.2008.05.015

Wang C, Wang Z, Qiao X, Li Z, Li F, Chen M, Cui H (2013) Antifungal activity of volatile organic compounds from *Streptomyces alboflavus* TD-1. FEMS Microbiol Lett 341(1):45–51. https://doi.org/10.1111/1574-6968.12088

Whitman W, Goodfellow M, Kampfer P, Busse HJ, Trujillo ME, Ludwig W, Suzuki KI (eds) (2012) Bergey's manual of systematic bacteriology, vol 5: The Actinobacteria. Springer-Verlag New York

Wildermuth H (1970) Development and organization of the aerial mycelium in *Streptomyces coelicolor*. Microbiology 60(1):43–50. https://doi.org/10.1099/00221287-60-1-43

Wildermuth H, Hopwood D (1970) Septation during sporulation in. Streptomyces coelicolor Microbiology 60(1):51–59. https://doi.org/10.1099/00221287-60-1-51

Xiong Z-Q, Tu X-R, Wei S-J, Huang L, Li XH, Lu H, Tu GQ (2013) The mechanism of antifungal action of a new polyene macrolide antibiotic antifungalmycin 702 from *Streptomyces padanus* JAU4234 on the rice sheath blight pathogen *Rhizoctonia Solani*. PLoS ONE 8(8):e73884. https://doi.org/10.1371/journal.pone.0073884

Yandigeri MS (2021) Role of actinomycetes in insect pest and plant Disease management. Biopestici Horticul Crops 17:152–172

Yandigeri MS, Malviya N, Solanki MK, Shrivastava P, Sivakumar G (2015) Chitinolytic *Streptomyces vinaceusdrappus* S5MW2 isolated from Chilika lake, India enhances plant growth and biocontrol efficacy through chitin supplementation against *Rhizoctonia solani*. World J Microbiol Biotechnol 31:1217–1225. https://doi.org/10.1007/s11274-015-1870-x

Yang M, Huang C, Xue Y, Li S, Lu L, Wang C (2018) Biofumigation with volatile organic compounds from *Streptomyces alboflavus* TD-1 and pure chemicals to control *aspergillus ochraceus*. Ann Appl Biol 173(3):313–322. https://doi.org/10.1111/aab.12465

Zhang Q, Yong D, Zhang Y et al (2016) *Streptomyces rochei* A-1 induces resistance and defense-related responses against *Botryosphaeria Dothidea* in apple fruit during storage. Postharvest Biol Technol 115:30–37. https://doi.org/10.1016/j.postharvbio.2015.12.013

Zhao S, Du C-M, Tian C-Y (2012) Suppression of *Fusarium oxysporum* and induced resistance of plants involved in the biocontrol of cucumber *Fusarium* wilt by *Streptomyces bikiniensis* HD-087. World J Microbiol Biotechnol 28:2919–2927. https://doi.org/10.1007/s11274-012-1102-6