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PLANT PATHOLOGY

Deciphering the Biocontrol Potential of *Streptomyces* sp. in Plant Disease Management: A Review

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ABSTRACT

Crop losses in agriculture are getting aggravated due to several abiotic and biotic factors including diseases caused by fungi, bacteria and viruses. Chemical fertilizers are applied to overcome which it is not a feasible method. Hence an alternative method should be found, to sought out the problems of using chemicals. Plant disease management using microbes is gaining interest recent days for replacing the chemicals. Among all, *Streptomyces* a gram-positive saprophytic bacterium stages a substantial role in combating plant diseases owing to its capability to induce or synthesis bioactive rich antimicrobial metabolites and enzymes. It is presumed that they are distributed wide in nature, but the rhizosphere region constitutes the most potential antibiotic producing organisms and are used as bio inoculant. Besides, it also increases the plant growth by producing plant growth promoting substances and suppress the disease through mechanism like antibiosis, mycoparasitism and nutrient competition; supplying of nutritive elements like iron, copper, phosphorus and sulphur; synthesis of plant hormones like IAA, cytokinin and siderophore. This review briefly illustrates about the role, mechanism, advantage and disadvantage of using *Streptomyces* spp. in plant disease management.

HIGHLIGHTS

- Actinobacteria are known antibiotic producers.
- They were effective against plant pathogens through various modes of action like mycoparasitism, competition, analysis and also through induction of defense proteins.
- Besides, they influence plant growth through production of growth hormones also.
- A collective documentation about the role of actinobacteria in plant growth and disease management is the need of researchers.

Keywords: *Streptomyces*, biocontrol, antibiosis, antimicrobial compound

The increasing demands on food production led to the dependence on chemical fertilizers and pesticides for increasing the productivity (Bhardwaj *et al.* 2014) and the decrease in productivity may be attributed to many reasons. Among all, pests and pathogens tops the list and the pathogen infection ranges between 20 to 40% (Savary *et al.* 2012). The extensive use of chemicals compounds lead to deposition of detrimental residues, development of fungicide resistance in plants, detrimental to non-targeted and beneficial microorganisms (Bharathi *et al.* 2004). Alternative measures like genetic engineering of plants for disease resistance, high yielding varieties are time consuming and demands strategies which can evade limitations of agricultural production (Rey and Dumas 2017). Hence, an emphasis on using microbes appears

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to be a sustainable solution for increasing the crop yield. Plant disease management through microbes plays a significant role because of its environment friendliness. Plant beneficial microbes are copious in the rhizosphere region which are used as bio inoculants and which has the capacity to maintain the soil environment by fixing the nitrogen, solubilizing the 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 *et al.* 2014).

Among all microbes, actinomycetes receives wide attention because of its potential antibiotic production which are used for controlling various plant pathogens. Mechanism employed by them includes mycoparasitism, competition for nutrients, production of hydrolytic enzymes and antimicrobial metabolites and regulation of plant defense. As per Bergey's Manual of Systematic Bacteriology (Whitman *et al.* 2012), actinomycetes renamed as actinobacteria of which *Streptomyces* is widely studied since it can be grown in laboratory on artificial media. About 10% of soil microflora is contributed by *Streptomyce*s sp. having antifungal, antibacterial, antiviral and antioxidant activities. 60 % of the antibiotic production is by *Streptomyces*, besides producing hormones like IAA and siderophore responsible for improvement of plant growth. In a nutshell, use of actinomycetes possessing antimicrobial activity might be an alternative for chemical fertilizers in plant disease management owing to its low cost of production, environment safety and reduction in usage of natural non-replenishable resources. Keeping in view the importance and potentiality, application of *Streptomyces* sp. as a bio inoculant and its mechanisms are reviewed here.

Actinobacteria

Actinobacteria sharing the characteristics of fungi and bacteria, are pervasive in soil, compost, atmosphere and fresh water basins in different depths globally. They belong to the Bacterial kingdom, under Actinobacteria phylum, in the Actinomycetes class, and actinomycetales order, with *Actinomycetaceae* family, a bacterium with high genomic G + C content (74 mol %) and gram-positive in nature (Elamvazhuthi and Subramanian, 2013). Malviya *et al.* 2009 and Gopalakrishnan *et al.* 2011 had isolated many such isolates from plant rhizosphere and among them *Streptomyces* spp. was extensively explored for their potential antimicrobial activity. Waksman and Henrici in 1943 familiarized *Streptomyces* for the first time (Goodfellow and Williams *et al.* 1983), 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, 16S rRNA analysis and DNA hybridization (Bhardwaj *et al.* 2014).

Actinobacteria produces an array of secondary metabolites with high commercial interest, among which genus *Streptomyces* tops in the production with discovery of actinomycin. Functions employed includes the degradation of organic substrates like proteins, fats, cellulose, humus and produce the characteristic earthy smell of soil due to geosmin content (Anandan *et al.* 2016).

Streptomyces is a major genus representing over 500 species, chemoorganotrophic, filamentous Gram +ve and not acid-fast organism. Majority of the species are mesophile (10-37^{o}C) while some are thermophile (45-55^{o}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 resistant to drought. Few reports illustrated that sandy loam and calcareous soil possess more *Streptomyces* than heavy clay soil. Production of substrate and aerial mycelium occurs in which substrate hyphae are 0.5 – 0.1 µm dia. As it ages, production of aerial mycelium begins resulting in formation of chain of spores (conidia) (Wildermuth 1970; Wildermuth and Hopwood 1970). The spores are formed by fragmentation and are arranged in helical, wavy or strait chains. The colonies are growing slow with initial smooth edges and progress in to crosswise mycelial threads later which appear velvety, powdery, floccose or granular with the typical earthy odour.

Isolation and characterization

Geographical factors like soil type, pH, temperature, organic content, farming, soil moisture and aeration determines the type and number of actinomycetes present. The actinomycetes could be isolated using several media *viz.*, Kenknight's agar medium, Starch casein agar medium, Actinomycetes Isolation Agar and Yeast extract-malt extract agar etc. Adegboye *et al.* (2012) isolated several strains from rhizosphere soil of cabbage spinach, sunflower, maize and onion on starch casein agar medium with 10µg/ml cycloheximide as and 25 µg /ml streptomycin as supplements to prevent the contamination by other bacteria and fungi. Similarly, from wheat and tomato rhizosphere soil, 98 plant growth promoting actinomycetes were isolated using the ISP 4 (Inorganic salt starch agar) medium (Anwar *et al*. 2016).

Actinomycetes had soil-like odour, pastel colours and stick into the agar (Kalyani *et al*. 2012). While growing on agar surface, the isolates produced a network of branching hyphae on both sides of agar (*i.e.,)* aerial mycelium on upper surface and substrate mycelium on lower surface (Sharma *et al.* 2014). The colonies are often leathery, compact with dry appearance on media covered with substrate and aerial mycelium of different colony colour, shape (Fig. 1).

Classical approaches for identifying actinomycetes includes physiological, morphological and biochemical methods based on Bergey's Manual of Determinative Bacteriology. Morphology of spore chain was classified into retinaculiaperti (RA), rectiflexibiles (RF), and spirales (S) (Madigan *et al*. 2012) (Fig. 2.).

Fig. 1: Growth of *Streptomyces* isolates on Starch casein agar medium; **(a)** aerial mycelium; **(b)** individual colony morphology; **(c)** substrate mycelium

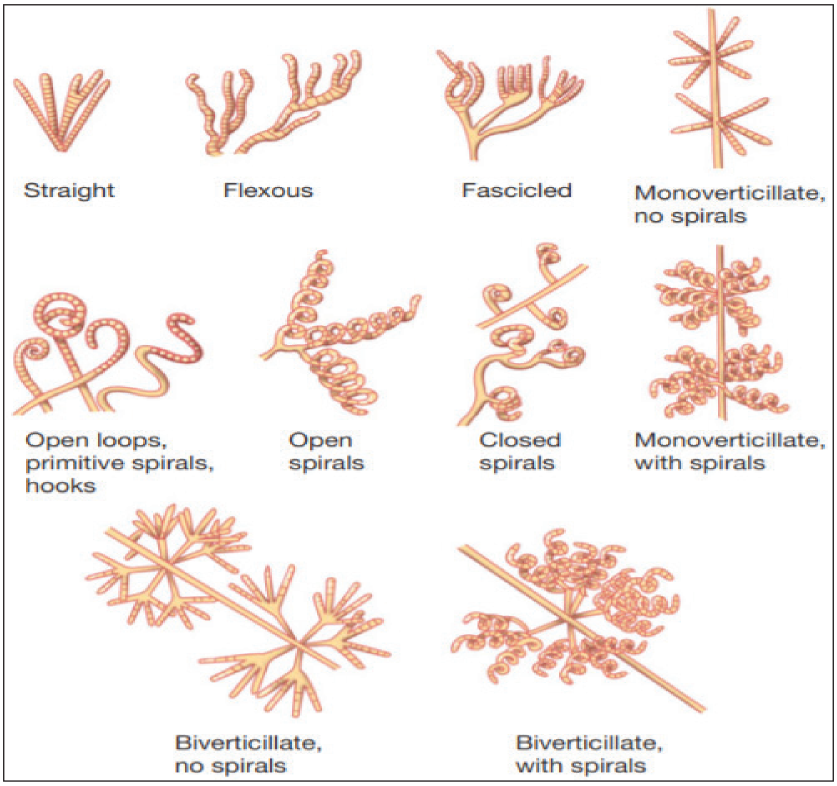


Fig. 2: Structure of spores produced by *Streptomyces* species (Madigan *et al.* 2012)

Physiological method of identification includes optimizing the range of temperature, pH and different concentrations of sodium chloride for growth of organism. Biochemical tests include nitrate reduction catalase production, hydrogen sulphide production, starch hydrolysis, gelatin liquefaction, Vogues-Proskauer test urease production, indole production, citrate utilization test and methyl red test (Sharma *et al*. 2014) while, molecular characterization is been done using the 16S rRNA universal primer 27F (5′-AGAGTTTGATCCTGGCTCA-3′) and 1492R (5′ACGGCTACCTTGTTACGACT-3′) and genus specific primer like Sm6F GGTGGCGAAGGCGGA, Sm5R GAACTGAGACCGGCTTTTTGA (Masand *et al.* 2018).

Streptomyces as a bio inoculant

Streptomyces spp. has the capacity of decomposing biopolymers like lignocellulose, starch, chitin in soil and water and organic matter. *Streptomyces* as bioactive compound became evident after the discovery of streptomycin which paved a way forward for detection of antimicrobial compounds. Malviya *et al.* 2009 and Gopalakrishnan *et al.* 2013 had isolated many number of actinomycetes from rhizosphere soil collected from various locations and screened for its novel microbial compounds. Among the actinobacteria, *Streptomyces* sp. alone contributed for 75% of antibiotic production used as agrochemicals and in pharmaceuticals (Berdy 2005). They have also gained importance in plant disease management through production of extracellular hydrolytic enzymes (Prapagdee *et al.* 2008; Joo, 2005; Elamvazhuthi and Subramanian 2013 and Gopalakrishnan *et al.* 2013). Formation of thread like filaments in soil is advantageous for colonizing the rhizosphere efficiently. Besides, they promote the plant growth, make nutrients available and antagonize with pathogens. They are exploited in production of antibiotics, bactericides, insecticides, fungicides, acaricides, and herbicides and applied as spore suspension, culture filtrate, wettable granules, wettable powder and emulsifiable concentrates.

Mechanism employed by *Streptomyces* against plant pathogens

Streptomyces species are capable of suppressing pathogen by performing functions as a source for bioactive compounds, extracellular enzymes and antibiotics (Fig. 3).

(i) Mycoparasitism / hydrolytic enzymes

In biocontrol of plant diseases, enzymes play a significant role like parasitism and antibiosis. Cell wall degrading enzymes like β-1,3-glucanase, chitinase, cellulase and protease are essential

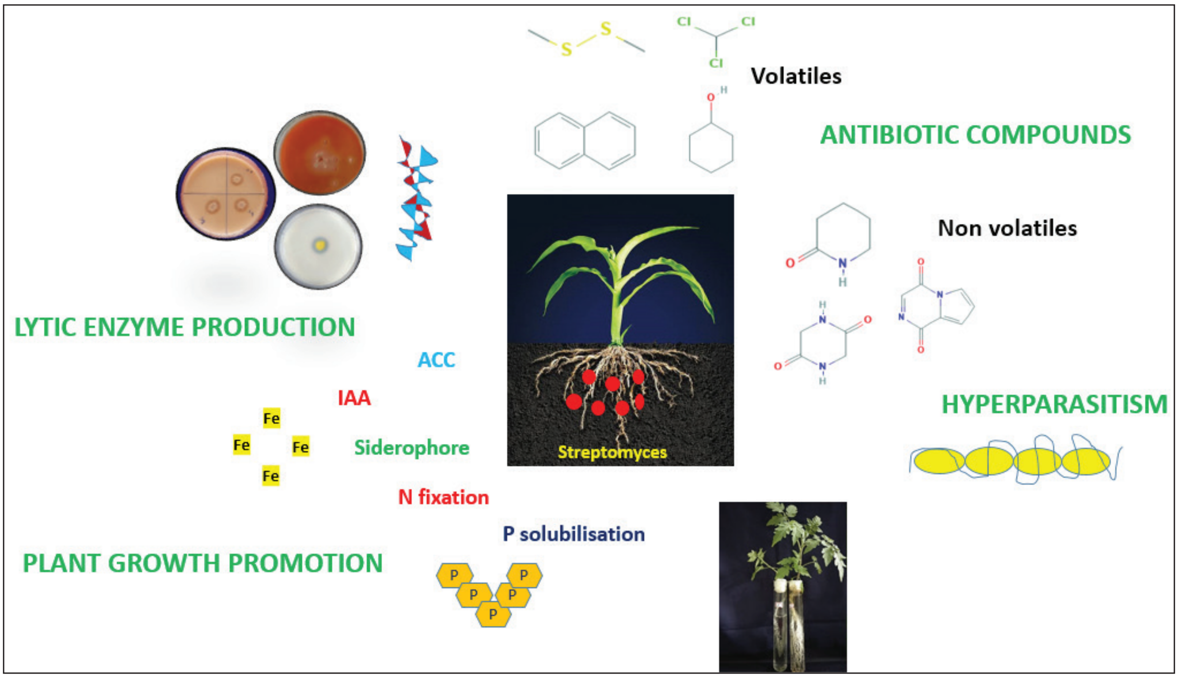


Fig. 3: Mode of action of *Streptomyces* against plant pathogens

Table 1: List of *Streptomyces* species used against different plant pathogens

Streptomyces	Disease	Pathogen	Reference
Streptomyces sp. S30	Tomato Damping-off	*Rhizoctonia solani*	Cao *et al.* (2004)
Streptomyces spp. 47W08, 47W10	Pepper Blight	*Phytophthora capsici*	Liang *et al.* (2005)
Streptomyces sp.	Sweet pea Powdery mildew	*Oidium* sp.	Sangmanee *et al.* (2009)
S. cavurensis NRRL 2740		*Colletotrichum gloeosporioides*	Intra *et al.* (2011)
S. toxytricini vh6	Tomato Root rot	*R. solani*	Patil *et al.* (2011)
Streptomyces spp.	Chilli Root rot, blight	*Alternaria brassiceae, C. gloeosporioides*	Srividya *et al.* (2012)
Streptomyces (CAI-24, CAI-121, CAI-127, KAI-32 and KAI90)	Chickpea Fusarium wilt	*Fusarium* spp.	Gopalkrishnan *et al.* (2013)
S. griseoviridis	Cucumber Damping-off	*Pythium* spp.	Junaid *et al.* (2013)
S. rochei ACTA 1551	Tomato Fusarium wilt	*Fusarium oxysporum* f.sp. *lycopersici*	Kanini *et al.* (2013)
Streptomyces spp.	Ginger Rhizome rot	*F. oxysporum* f. sp. *zingiberi*	Manasa *et al.* (2013)
S. hundungensis strain MBRL 251	Rice – Blast, brown spot, sheath blight	*Bipolaris oryzae, Curvularia oryzae, Fusarium oxysporum, Pyricularia oryzae, Rhizoctonia solani and Rhizoctonia oryzae-sativae*	Nimaichand *et al.* (2013)
Streptomyces sp. CBE	Groundnut Stem rot	*Sclerotium rolfsii*	Adhilakshmi *et al.* (2014)
Streptomyces spp.	Tomato Damping-off	*R. solani*	Goudjal *et al.* (2014)
S. aurantiogriseus VSMGT1014	Rice Sheath blight	*R. solani*	Harikrishnan *et al.* (2014)
S. misionensis NBRC	Rice Brown spot, Sheath blight	*Helminthosporium oryzae, R. solani*	Poomthongdee *et al.* (2015)
Streptomyces vinaceusdrappus S5MW2	Tomato Root rot	*R. solani*	Yandigeri *et al.* (2015)
Streptomyces rochei A1	Apple	*Botryosphaeria dothedia*	Zhang *et al.* (2016)
Streptomyces sp. *3-10*	Strawberries	*B. cinerea*	Lyu *et al.* (2017)
Streptomyces spectabilis NBRC 13424	Banana	*C. musae, C. gloeosporioides*	Chen *et al.* (2018)
Streptomyces strain PC 12, *Streptomyces* strain D 4.1, *Streptomyces* strain D 4.3 and *Streptomyces* strain W1	Rice	*Pyricularia* sp.	Chaiharn *et al.* (2020)

for antifungal activities (Haggag and Mohamed 2007). Actinobacteria are potential producers of β-1, 3-glucanase, chitinase, amylase, pectinase, cellulase, xylanase, lipase and protease and are specifically produced from actinomycetes isolated from agricultural soil (Sonia *et al.* 2011). Glucanase and chitinase were leading to complete dissolution of *Sclerotium rolfsii*, *Sclerotinia minor*, *Aspergillus* and *Fusarium oxysporum* (Hassan *et al.* 2011). Two hundred and eighty-three chitinolytic actinomycetes were isolated from rhizosphere soils of Sisaket Province and Ubon Ratchathani, Thailand was isolated by Pattanapipitpaisal and Kamlandharn (2012), among which 13 isolates showed potentiality for inhibiting the fungal growth emphasizing its usage as biocontrol agent. Srividya *et al.* (2012) reported β-1, 3 and β-1, 4 glucanase, chitinase, protease 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. has the capacity to depolymerize it. Hence it could be exploited as a promising tool in biocontrol either directly or indirectly by usage of purified proteins (Sonia *et al.* 2011). Chitinase producing isolates from chilli rhizosphere 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).

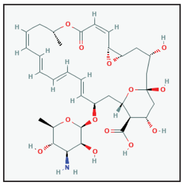
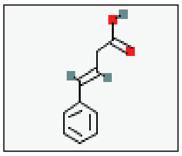
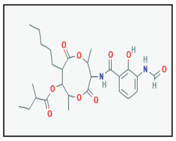
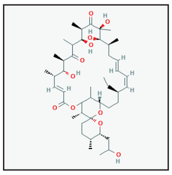
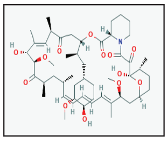
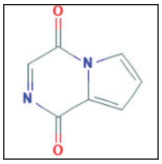
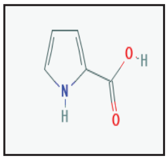
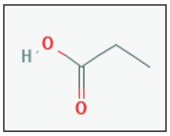
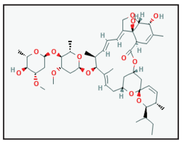
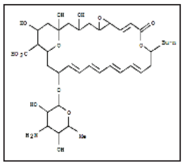
(ii) Antibiosis

Actinobacteria have the capability to produce many volatiles, toxins and antibiotics. Among actinomycetes *Streptomyces* are potential producer of several secondary metabolites having capability to act as fungicides against the plant diseases besides ensuring environmental safety (Siupka *et al.* 2021). *S. padanus* Strain JAU4234 which produced fungichromin, actinomycin X2 and antifungalmycin 702 and showed antifungal activity by changing the structure of cell membranes and the cytoskeleton in *Rhizoctonia solani* in addition to interaction with the 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 which were showing antibacterial activity against *Staphylococcus aureus*, *Micrococcus lutea*, *Bacillus subtilis*, *B. pumilus*, *Klebsiella pneumonia*, *Escherichia coli*, *Pseudomonas aeruginosa*, *Saccharomyces cerevisiae*, *Candida albicans* and antifungal activity against *Aspergillus flavus*, *A. niger*, *A. fumigatus*, *Fusarium oxysporum*, *Rhizoctonia solani*, *Alternaria alternata*, *Botrytis fabae* and *Penicillium chrysogenium* (Atta *et al.* 2015). Similarly, the antibiotic compounds geldanamycin, guanidylfungin A and nigericin produced by *S. violaceusniger* YCED9 were showing antifungal activity against *Phytophthora, Pythium* and *Fusarium* spp. besides producing the chitinases and β-1,3-glucanase enzymes (Trejo-Estrada *et al*. 1998). Polyoxins B and D obtained from *S. cacaoivar* functions by inhibiting the chitin syntheses (Isono *et al*. 1965). Mildiomycin from *Streptoverticillium rimofaciens* inhibits protein biosynthesis in powdery mildew (Harada and Kishi 1978). Polyene from *Streptomyces plumbeus* effective against *Botrytis cinerea* (Kim *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 *et al*. 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* 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.* 2018) 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 radicles (Morales-González, 2013) exhibiting antioxidant activity. Propyl ester of octadecanoic acid produced by *S. albolongus* S9 was highly inhibitory to *Corynespora cassiicola* causing spot disease in tomato (Devi and Rao 2017).

Volatile organic compounds are diffusible and low molecular weight compounds and produced by many *Streptomyces* spp. exhibit strong antifungal activity. The compounds produced belonged to aldehydes alkanes, aromatic hydrocarbons, alcohols, alkenes, ketones, furans, esters, and ethers. Volatiles from *S. platensis* strain F-1, established resistance against *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 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).

Table 2. List of antimicrobial compounds of different *Streptomyces* screened against various plant pathogens

Metabolite	Structure	Organism	Disease	Reference
Natamycin		*S. lydicus* strain A01	*Fusarium oxysporum, Botrytis cinerea, Monilinia laxa*	Lu *et al.* (2008)
4-Phenyl-3-butenoic acid		*S. koyangensis* strain VK-A60	*Colletotrichum orbiculare, M. grisea, Pythium ultimum*	Lee *et al.* (2006)
Antimycin A17		*Streptomyces* sp. GAAS7310	*Curvularia lunata, Rhizopus nigricans*, and *Colletotrichum nigrum*	Chen *et al.* (2005)
Oligomycins A and C		*S. diastaticus*	*Aspergillus niger, Alternaria alternata, B. cinerea,* and *P. capsici*	Yang *et al.* (2010)
Rapamycin		*S. diastaticus*	*Aspergillus niger, Alternaria alternata, Botrytis cinerea and Phytophthora capsici*	Yang *et al.* (2010)
Pyrroles (Pyrroles [1,2-a] pyrazine-1,4-dione		*S. diastaticus*	*Aspergillus niger, Alternaria alternata, Botrytis cinerea and Phytophthora capsici*	Yang *et al.* (2010)
1H-Pyrrole-2-carboxylic acid (PCA)		*S. griseus* H7602	*P. capsici*	Nguyen *et al.* (2015)
Propanoic acid		*S. lavendulocolor* VHB-9	*M. grisea*	Bindu *et al.* (2017)
Avermectins		*S. avermitilis*	*Fusarium oxysporum*	Cheng *et al.* (2018)
Lucensomycin		*S. plumbeus* strain CA5	*B. cinerea*	Kim *et al.* (2020)

VOCs secreted by *S. alboflavus* TD-1 possess 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).

Against bacterial pathogens

S. termitum ATC-2 produced an antimicrobial compound aloesaponarin II which exhibited antimicrobial activity against rice bacterial blight disease (Donghua *et al.* 2013). Similarly, Mingma *et al*. (2014) reported the inhibition of *Xanthomonas campestris* pv. *glycines* causing bacterial pustule on soybean by *Streptomyces* sp. strain RM 365 and *Pectobacterium carotovorum* and *P. atrosepticum* causing soft rot of potato was reduced up to 90 per cent by *Streptomyces* sp. strain OE7 (Baz *et al.* 2012).

(iii) As a root colonizer and defense activator

The rhizosphere is a repository for all chemical and biological interactions in the soil matrix, which contains a diversified groups of bacteria including beneficial and harmful. (Raaijmakers *et al.* 2009; Compant *et al.* 2010; Glick 2012). One of the essentialities of biocontrol agents is to colonize the roots effectively in which higher colonization leads to higher efficacy against plant pathogens. Deleterious microbes compete for nutrients whereas beneficial microbes mobilize the plant nutrients and protect from plant diseases (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.* (2018) 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 thickness of cell wall, PPO oxidizes phenols to quinone, PAL enhance the production of phenolic compounds lignans and phytoalexin which promotes systemic resistance in plant (Wang *et al*. 2013).

(iv) Plant growth promotion

As like other PGPRs, *Streptomyces* also has the capability to promote plant growth and increase the crop yield through acquiring nutrients or by secretion of growth regulators. The plant biomass got enhanced by the inoculation of *Streptomyces* strains into plants like tomato wheat, sorghum and rice (Palaniyandi *et al.* 2011). Plant growth promotion was achieved through some mechanisms including phosphate solubilization N_2 fixation, ACCdeaminase production, sulphur oxidation and acquisition of iron for plant growth promotion (Jaemsaeng *et al.* 2018). Tomato plants inoculated with 1-aminocyclopropane-1-carboxylate deaminase (ACCD) producing endophytic *Streptomyces* sp. GMKU 336 showed resistance during waterlogged conditions (Jaemsaeng *et al.* 2018). Five isolates including *Streptomyces* sp., *S. tsusimaensis*, *S. caviscabies*, *S. setonii* and *S. africanus* were highly effective against chick pea wilt caused by *F. oxysporum* f. sp. *ciceri* besides promoting plant growth ability on Sorghum and rice crops (Gopalakrishnan *et al*. 2013).

Phosphate solubilization

Though phosphorus plays an important role in plant growth, its availability is limited in soil and hence supplemented with chemical fertilizers. Due to its hasty immobilization, majorily they are leached off and proportionately a little is available for the plants (Shigaki *et al.* 2006). Being a potential root colonizer and an agent for altering insoluble phosphorus in to available (Hamdali *et al.* 2008) through production of solubilizing acids like propionic acid, lactic acid, citric acid, gluconic acid, malic acid, succinic and oxalic acids, the filamentous *Streptomycetes* sp. are given with due attention and hence, the *S. griseus* and other *Streptomyces* sp. are potentially used as a phosphate solubilizer in phosphorus deficient soils (Jog *et al.* 2014).

Siderophore production

Proliferation of pathogenic micro-organisms is prevented by the siderophore producing rhizobacteria and which mostly belong to *Streptomyces Serratia Pseudomonas Rhizobium* and *Bradyrhizobium* genera (Kuffner *et al.* 2008). *Streptomyces* spp. produce hydroxymate type siderophore that protects the plants against pathogens (Khamna *et al*. 2009). *Streptomyces rochei* IDWR 19 which produces a hydroxymate siderophore at the rate of 34.17 mg/l (Jog *et al*. 2014).

IAA production

Plant growth promotion is also due to production of growth regulators. The principal form of auxin is IAA which performs various functions like cell differentiation, elongation, division, development of embryo and fruits, vascular tissue differentiation, organogenesis, root patterning, apical hook formation and apical dominance (Khamna *et al.* 2009). *Streptomyces* species like *S. rochei*, *S. rimosus* and *S. olivaceoviridis* from the tomato rhizosphere, have the potential to produce IAA and improve plant growth by increased seed germination, root elongation and root dry weight (El-Tarabily and Khaled 2008).

Streptomyces has been found to produce natural auxin (IAA) (El-Tarabily and Khaled, 2008; Khamna *et al*. 2009). Plant growth has also been observed to be aided by gibberellins and cytokinin-like compounds generated by *S. rimosus*, *S. olivaceoviridis*, and *S. rochei* (Palaniyandi *et al*. 2011). Auxins also supports in stimulation of root hairs, lateral root formation and sugar secretion which in turn plays an important role in early microbial root colonization. *Streptomyces* sp. which produces IAA and siderophore also increases the availability of trace elements like zinc, iron besides stimulating the growth and elongation of plant roots (Cakmakci *et al.* 2006).

Commercially available strains

Ten species of *Streptomyces* have been registered as commercial goods (Vurukonda *et al*. 2018), while a few more are in the early stages of commercial formulation development. The actinobacterial formulations Mycostop and Actinovate have been commercially exploited for a long time. Owing to the presence of antifungal antibiotic, aromatic heptaenepolyene, Mycostop (*S. griseoviridis* K61 strain isolated from sphagnum peat) and registered in Canada, the European Union, and the United States for use against seed and soil borne fungal diseases. Similarly, the Actinovate made from the *S. lydicus* WYEC 108 strain suppresses *Pythium ultimum* and *Rhizoctonia solani* growth besides promoting plant growth. Actinovate have also been used to prevent *Fusarium*, *Phytophthora*, *Verticillium*, and foliar diseases such powdery and downy mildew (Vurukonda *et al*. 2018). In United States and Ukraine, Blasticidin-S against rice blast and Kasugamycin against Phytophthora led root rot and leaf spot in various crops have been registered, respectively (Aggarwal *et al*. 2016). The wettable *Streptomyces* sp. Di-944 formulation prevents the damping off disease of tomatoes caused by *Rhizoctonia solani* (Sabaratnam and Traquair 2002).

Advantages and disadvantages of *Streptomyces* bio-inoculant

Advantages

The metabolites from actinomycetes are naturally occurring and gaining importance in plant disease management. Considering its frequency, dominance and potential as agro chemical it could be marketed commercially (Solanki *et al*. 2016).

- Less harmful and eco friendly;
- Targets the specific organism and decomposes quickly;
- Supplies micronutrients and balances the soil nutrient cycle;
- Regulates plant metabolism against diseases;
- Efficient colonizer of roots and supports colonization of mycorrhiza.

Disadvantages

- Storage is a major problem;
- Success rate is low;
- Compared to other bacterial inoculants, proliferation rate is slow.

CONCLUSION

Considering the potentiality and various mechanism employed by *Streptomyces* sp. it could be used as a bio inoculant for disease management. The constraint is that all the strains performing better under *in vitro* condition, cannot perform in the same manner under *in vivo* condition. Hence efficient technique must be developed to identify the strain performing well under both conditions.

Future perspectives

Microorganisms generally play a vivacious role in plant disease management. Among those, *Streptomyces* have been focused by researchers and commercial products are made with its metabolites which symbolises its use as a bio inoculant for disease control. To date only active *Streptomyces* sp. have been isolated from rhizosphere soil. Research should be focused on identifying novel rare *Streptomyces* sp. from unexplored environments which will have immense potential of producing antibiotics. Research on methods to elute the identified antimicrobial compounds should be studied to make it available commercially. In addition, optimization of suitable carrier, avoiding deleterious metabolites and genetic engineering of the effective strain will be helpful in making commercial product for agriculture purpose.

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