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# An update about plant growth promoting *Streptomyces* species

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**ABSTRACT**

Beneficial microorganisms have profound positive impacts on various human activities, including medicinal, pharmaceutical, and other biotechnological applications. This review provides an update about the potential of *Streptomyces* species as promising plant promoters because of their various roles as biofertilizers, biostimulators, biocontrol agents, and bioremediates. It also briefs the numerous mechanisms tackled by *Streptomyces* species, including the synthesis of plant growth regulators, siderophore production and secretion of the volatile compound to improve crop productivity. The percentage of increment in yield of different plants on inoculation with *Streptomyces* species is also outlined. Plant growth-promoting *Streptomyces* species are collectively *Streptomyces* highlighted as drivers for food security to satisfy global food demand.

## 1. INTRODUCTION

The continuous increase in the human population is proportional to the demand for food supply and living space. Accordingly, anthropogenic activities to overcome food and space scarcity have negatively influenced the natural environment. Consequently, numerous environmental problems can be witnessed globally, including pollution, global warming, limited availability of water, and the greenhouse effect [1]. Plants, the primary producers in food chains, are most significantly affected by changing environments and become more susceptible to various diseases under environmental stresses. On the other hand, the need to improve crop yield to sustain the food supply introduced the use of chemical fertilizers. The application of these fertilizers became common and was adopted globally, but it was later revealed for its hazardous effects on crops and contribution to environmental pollution [2].

The use of chemical fertilizers altered the soil's properties, such as soil acidification and pH balance, and decreased crop productivity, that is, stunted plant growth in later stages of the plant life cycle [2]. Moreover, the consumption of these chemically fertilized plants caused humans to develop a variety of diseases, including cancer and problems with the liver, kidney, or lung functions [3]. The advancement in scientific tools and techniques, however, enabled the discovery of plant growth promoting bacteria (PGPB) and opened avenues for their use as a "biological fertilizer" in developing a balanced and safe strategy to promote plant growth. Among these PGPB, *Streptomyces* spp. (PGPS) are particularly identified to enhance the plant's growth while minimizing the adverse effects of abiotic stresses and diseases [4]. *Streptomyces* spp. are also known to produce various antibiotics that inhibit the growth of pathogens.

*Streptomyces* belong to the family *Streptomycetaceae* and display a wide range of morphological features, such as helix chains, straight and wavy structures due to the fragmentation of filaments [4]. This genus has more than 900 species and 50 subspecies and can exist in both marine and terrestrial environments [5]. *Streptomyces* are Gram-positive bacteria, with a high (69–78%) ratio of cytosine and guanine [6]. A plethora of research has highlighted the numerous benefits of *Streptomyces* species, including their role as a biocontrol agent in eliminating microbial diseases, as an effective rhizosphere colonizer, and as a plant growth promotor [7]. For instance, *Streptomyces* species isolated from herbal vermicompost control the spread of *Fusarium* wilt caused by fungus *Fusariumoxy sporum* in chickpeas. Moreover, species such as *Streptomyces atrovirens*, *Streptomyces lydicus*, *Streptomyces rochei*, and *Setaria viridis* were exclusively identified to promote plant growth [8]. The plant growth-promoting properties of *Streptomyces* are strongly related to the production of phytohormones and solubilizing phosphates, which strengthen the immune system response of plants and inhibit fungal growth [8]. These bacteria also facilitate the decomposition of dead organic matter, degradation of adenine, esculin, gelatin, hypoxanthine, starch, and L-Tyrosine, and reduction of nitrates to nitrites [8]. They can effectively control plants' pathogens by synthesizing extracellular proteins, siderophores, antibiotics, and other valuable products [9].

## 2. PROPERTIES OF *STREPTOMYCES* AS A PROMOTER OF PLANT GROWTH

Different species of *Streptomyces* have the property to produce indole acetic acid (IAA) and aminocyclopropane-1-carboxylic

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acid (ACC) deaminase activity, which facilitates and promotes plant growth [9]. The production of IAA, that is, the main auxin among phytohormones, stimulates plant growth and developmental processes by ensuring cell division, the release of saccharides from plant cell walls during cell elongation, organization of new cells into tissues with different functions, and allowing apical dominance [10]. It was also found to respond to the invasion of pathogens, light, and gravity. IAA is also known to stimulate the formation of lateral roots and root hair to enhance water absorption by plant [10].

Along with being directly utilized for plant growth promotion, such as cell division and elongation to enhance shoots and roots development, IAA may act as a precursor molecule for the production of ACC synthase, which ultimately is required for the synthesis of ethylene, that is, another crucial phytohormone [11]. Moreover, a significant proportion of the ACC produced within the plant may diffuse outwards through the roots, leaves, and seeds, which is then cleaved by the activity of ACC deaminase enzyme of particular bacteria in the surrounding. Thus, the microbial deaminase is wholly responsible for the cleavage of ACC, that is, a precursor of the plant ethylene that will turn into ammonia and $\alpha$-ketobutyrate [11]. Thus, ACC is a non-protein amino acid that functions as ethylene's direct precursor. These physiological mechanisms are crucial for biocontrol properties of *Streptomyces* such as antifungal activity of *Streptomyces hydogenans* was found associated with the high rates for synthesizing IAA and thoroughly utilized ACC deaminase [11,12].

The IAA and ACC deaminase are significant features of PGPR, where *Streptomyces* species is described as rhizosphere colonizing bacteria. These bacteria either reside in the soil constituting soil microbiota and colonizing plant roots, or may enter the tissues of plant roots as endophytes, where they produce IAA and ACC deaminase to benefit plant development [13]. The synergistic role of IAA and ACC deaminase in promoting plant growth is highlighted by the established understanding that signal transduction pathways for IAA synthesis are inhibited in the presence of higher levels of ethylene. Thus, ACC deaminase activity to the lower the contents of ethylene acts synergistically to promote plant growth by stimulating IAA production. Consistent to this understanding, scientific evidence was provided that plant growth promoting *Streptomyces* species mainly synthesize both IAA and ACC deaminase [14]. The beneficial effects for collective production of IAA and ACC deaminase have been reported to improve growth of tomato plant [15].

These bacteria, which were probably drawn to plants by either dead root material in the soil or roots' exudates that had accumulated over time, eventually ingest various nutrients from the plant's roots, including amino acids such as tryptophan, polyamines, sugars, and organic acids, to grow and multiply [16]. The tryptophan molecules, in particular, ensure synthesis of IAA in bacteria, which in turn stimulates production of IAA in host plant [16]. The examples include *Streptomyces filipinensis* and *S. atrovirens* which sustain agricultural practices by encouraging the growth of various plant species [17]. However, the ability to produce ACC synthase varies among different species such as *S. filipinensis* was found to have a higher capacity to produce ACC

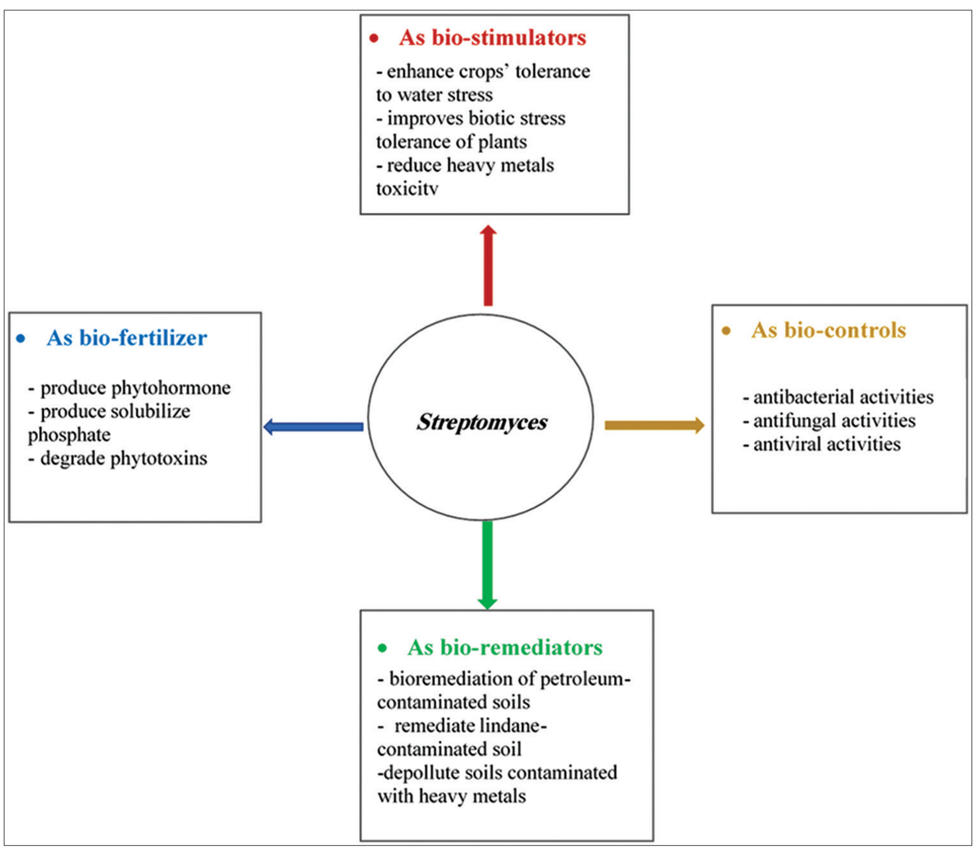


**Figure 1:** *Streptomyces* spp. as bio-stimulators, bio-controls, bio-fertilizers, and bio-remediators for plant growth [9,26,27]. Biostimulation is mediated via increasing plant growth and enhancing plant resistances to abiotic stressors. Biofertilization is mediated through producing of phytohormones, solubilizing P, and degrading phytotoxins. Biocontrol is mediated through production of antimicrobial agents. Bioremediation is mediated through removal of toxic pollutants from the environment.

**Table 1**: *Streptomyces* as plant growth-promoters. The name of the species (*Streptomyces* and plant) and the proved activities are highlighted.

| ***Streptomyces* species** | **Improved plant species** | **PGP activities** | **Reference** |
|---|---|---|---|
| *Streptomyces* sp (XN-04) | *Gossypium herbaceum* (Cotton) | - IAA biosynthesis<br>- Production of extracellular hydrolytic enzymes<br>- Production of diffusible antifungal metabolites | [1] |
| *Streptomyces* spp. Neau-S7GS2 | *Glycine max* (Soybean) | - Solubilization of inorganic phosphate<br>- Production of 1-aminocyclopropane-1-carboxylate (ACC) deaminase<br>- Biosynthesis of indole acetic acid (IAA) | [50] |
| *Streptomyces anulatus* S37 | *Vitis vinifera* (Grapevine)<br>*Phaseolus vulgaris L* (Bean)<br>*Cicer arietinum* (Chickpea) | - ACC deaminase<br>Production<br>- Iron chelation,<br>- Phosphate solubilization | [9] |
| *Streptomyces filipinensis* | *Solanum lycopersicum L* (Tomato plant) | - Auxin production<br>- ACC deaminase production<br>- Solubilization of inorganic phosphate | [45] |
| *Streptomyces atrovirens* | *Solanum lycopersicum L* (Tomato plant) | - ACC deaminase production<br>- Gibberellin biosynthesis<br>- Siderophore production | [45] |
| *Streptomyces spiralis* | *Cucumis sativa* (Cucumber) | - IAA production<br>- Improved growth<br>- Improved yield of cucumber | [45] |
| *Streptomyces scabiei* | *Solanum tuberosum* (Potato) | - IAA production<br>- Biosynthesis of Thaxtomin<br>- Secretion of secretes a novel virulence protein | [8] |
| *Streptomyces acidiscabies* | *Solanum tuberosum* (Potato) | - Auxin Production<br>- Siderophores production<br>- Alleviates iron deficiency | [49] |
| *Streptomyces aurantiogriseus* | *Oryza sativa* (Rice) | - IAA production<br>- Enhances phosphate solubility<br>- Siderophore production | [51] |
| *Streptomyces rochei* | *Triticum aestivum* (Wheat) | - Auxin/IAA production<br>- Gibberellic acid production<br>- Siderophore production | [52] |
| *Streptomyces thermolilacinus* | *Triticum aestivum* (Wheat) | - Improves phosphate solubilization<br>- Production of siderophore<br>- IAA synthesis | [53] |
| *Streptomyces hydrogenans DH16* | *Vigna radiata* (green gram) | - Biosynthesis of indole acetic acid<br>- Insecticidal activity against *Spodoptera litura*<br>- Antifungal antagonist | [54] |
| *Streptomyces griseoviridis strain K61* | *Triticum aestivum* (Wheat) | - Increases phosphate solubility<br>- Indoleacetic acid production<br>- Improves the bioavailability of trace elements such as iron and zinc | [55] |
| *Streptomyces lydicus strain WYEC 108* | *Pisum sativum* (pea plant) | - Nitrogenase activity<br>- Improves assimilation of iron in nodules<br>- Produces chitinolytic enzymes to inhibit pathogens | [9] |
| *Streptomyces* spp. *CIMAP- A1* | *Geranium* (*Pelargonium*) | - Produce siderophores<br>- Produce indole-3-acetic acid<br>- Produce secondary metabolites to resist numerous fungi | [55] |
| *Streptomyces tricolor Strain HM10* | *Musa balbisiana* (banana) | - Enhanced production of siderophores<br>- Increase IAA biosynthesis<br>- Improves phosphate solubilization. | [56] |
| *Streptomyces hygroscopicus* | *Oryza sativa* (Rice) | - Produce indole-3-acetic acid<br>- Improves adventitious roots formation<br>- Siderophore production | [57] |
| *Streptomyces olivaceoviridis* | *Triticum aestivum* (Wheat) | - Accelerates the emergence of adventitious roots<br>- Enhances biosynthesis of gibberellin<br>- Produces cytokinins | [58] |

when compared to that of *S. atrovirens*, and therefore different effects of these species on plant growth were recorded. Similarly, *Streptomyces albulus* revealed that due to its antifungal activity against sclerotium rot in mungbean, it has the potential as a biocontrol agent [18]. Likewise, *Streptomyces alfalfae XN*-04 creates several siderophores, such as coelichelin, enterobactin, and mirubactin, which are influential plant growth promoters and disease suppressants [19].

Utilizing *Streptomyces* species, that is, plant growth-promoting bacteria to improve agricultural yield is the need of era and to achieve sustainable development goals such as zero hunger for increasingly world population. The current disparities in the growing population and food scarcity are expected to be intensified by the year 2050 [20]. Therefore, the role of agriculture as a capstone resource in providing food requirements to humankind cannot be neglected. The efforts to improve crop yield and soil fertility by applying chemical fertilizers are an outdated approach with more harmful effects on the biotic and abiotic factors of environment. However, exploiting plant growth-promoting *Streptomyces* (PGPS) to sustain plant growth and production has become green, efficient, and cost-effective. PGPS represent a significant subset that comes under the umbrella of PGPB. PGPB are taxonomically diverse including *Bacillus* spp. [21], *Enterobacter* [22], *Brevibacterium casei* [23], *Streptomyces, Sinorhizobium* [24], and *Pseudomonas* [25]. These bacteria vary in their mode of action, and therefore have utilizations as biofertilizers, biostimulators, biocontrol agents, and bioremediators. PGPS display their beneficial roles as either one or more of these four categories.

## 3. *STREPTOMYCES* AS BIOFERTILIZERS

*Streptomyces spp.* as bio-stimulators, bio-controls, bio-fertilizers, and bio-remediators for plant growth [Figure 1]. The plant growth-promoting activities of *Streptomyces* are presented in Table 1. *Streptomyces. Streptomyces violaceusniger* has been demonstrated to colonize plant rhizosphere while assisting the growth and development of the host plant by enhancing the functionality of nearby microorganisms such as nitrogen-fixing bacteria and stimulating the contents of phytohormones [28]. *S. violaceusniger* performed at its best, with an acetylene reduction assay (ARA) value of 4351.0 nmol/24 h, when tested for *in vitro* nitrogen fixation potential [28]. In addition, because this species can solubilize phosphate, using it ensures that phosphate is available to plant roots and helps potato plants fight potato scabs [28]. Recent research [29] revealed the production of biofertilizers using *Bradyrhizobium* and *Streptomyces griseoflavus* strains, which promoted the growth of roots and shoots in the mung bean, soybean, and cowpea. In addition, it was discovered that an increase in nodulation formation, nitrogen fixation, uptake of NPK (nitrogen, phosphorus, and potassium), and seed yield was particularly noticeable in mung beans and soybeans [29]. *Streptomyces* has been discovered to establish a colony in the rhizosphere or tissue of plants and maintain a successful symbiotic relationship that furthers the growth of the plants [30]. The author has noted that the production of siderophores and the synthesis of plant growth regulators like IAA were both carried out by *Streptomyces* [30]. Mannitol and asparagine have also been shown to be crucial for increasing IAA production because they give *Streptomyces'* hyphal growth the nutrients it needs, which in turn helps the plants get the nutrients they need from the environment [31].

*Streptomyces fradiae* was found to synthesize significant concentrations of IAA, including 82 g/mL at a concentration of 2 g/L of tryptophan [32]. The author also mentions the potential for produced IAA to have a long shelf life and future applications for regulating plant growth to lessen the financial burden on agricultural yield [32].

## 4. *STREPTOMYCES* AS BIO-CONTROL

Various *Streptomyces* spp. are well-documented to be used as effective biocontrol agents protecting various economic plant species against microbial diseases [Table 2]. It has been demonstrated that *Streptomyces* species have effective biocontrol capabilities against *Fusarium* and *Verticillium.* Researchers discovered that *Streptomyces* mhcr0816 and mhce0811 release phosphate through gluconic acid and malic acid reactions [30]. As a biocontrol agent, *Streptomyces* is primarily known for its ability to produce potent volatile compounds and metabolites and antibiotics that have antipathogenic properties [30]. For instance, substances released from *Streptomyces coelicolor*, *S. violaceusniger* YH27A strain, and *S. violaceusniger* YCED-9 control activation of hyphal development and regulate stress metabolite. These substances include siderophore, chitinase, antifungal nigericin, and antibiotic geldanamycin [31]]. *Streptomyces griseus* on *Rhizoctonia solani, S. rochei* ACTA1551 on *Fusarium*, *Streptomyces felleus* YJ1 on *Sclerotinia sclerotiorum,* and other effective *Streptomyces* species have biocontrol activities [32]. However, one of the successful uses for *Streptomyces'* biocontrol ability was noted in the case of rice plants [32]. This study demonstrated the biocontrol potential of *Streptomyces* strains (A20 and 5.1) in preventing the spread of pathogenic bacteria by producing a variety of secondary active metabolites and thereby preventing *Burkholderia glumae*, a severe bacterial threat to rice yield by causing panicle blight in rice plants, from growing and spreading [32]. While two of the isolates used in the study (A20 and 5.1) displayed antibacterial and antifungal activities against a variety of pathogenic microbes, it was discovered that the third isolate only had antifungal activity [32].

*Streptomyces* has antimicrobial activity, with a MIC of 0.63–10% for bacteria and 0.63–3.3% for fungi. In addition, it was discovered that the fermented broth of these strains had biocontrol activity against *Xanthomonas euvesicatoria* leaf spot and *Ralstonia solanacearum* tomato bacterial wilt [33]. Streptomycin-resistant organisms, such as *Pectobacterium carotovorum* subsp. *Carotovorum*, the culprit of soft rot in Kimchi cabbage [33].

## 5. SIDEROPHORE PRODUCTION

It was discovered that the stress hormone affected the *Streptomyces*' metabolism during the siderophore's production [34]. The production of angucyclines was also found to increase the moiety of catechol. In addition, it was discovered that substances such as catechin, dopamine, levodopa, and norepinephrine positively affect siderophore production [34].

*S. fradiae* displayed a moderate effect as an antibiotic agent against *Clostridium* due to the production of siderophores such as Fradiamine [35]. In addition, the marine environments that produced the streptobactin, benarthin, and *Streptomyces* spp. YM5-799 are used to produce a siderophore [35]. In addition, two biosynthetic gene cluster substances identical to desferrioxamine BGC and salinichelin or albachelin control siderophore production [35].

## 6. VOLATILE COMPOUND SECRETION

*Streptomyces* species have antifungal, antibacterial, and plant growth-promoting properties that can be attributed to a wide range of volatile organic compounds [36]. It was discovered that the production and secretion of the volatile compound from the *Streptomyces* species depend heavily on salicylic acid and the ethylene pathway [37]. Different environmental factors, such as pH level, nutrient availability, and stress condition, especially in *Streptomyces*, facilitate

**Table 2:** *Streptomyces* use as bio-controls. Source, species, nature of the biocontrol agents, and the disease are illustrated.

| ***Streptomyces* species** | **Source** | **Bio-controls** | **The disease** | **References** |
|---|---|---|---|---|
| *Streptomyces mhcr0816* | *Rhizospherium* Soyabean (Rhizosphere of soybean) | Antifungal and antibacterial activity against fusarium and Verticillium | Wilting of roots, *Fusarium oxysporum* induced wilting, *Verticillium spp.* induced wilt | [9] |
| *Streptomyces griseus* | Radices mung (Root of mung) | Antifungal against *Rhizoctonia solani* | Rhizoctonia root rot | [9] |
| *Streptomyces rochei ACTA1551* | Radix colonia *Brassica rapa* subsp. Pekinensis (root colony of *Brassica rapa* subsp. Pekinensis) | Antifungal against *Colletotrichum* sp | Anthracnose, Leaf spots | [36] |
| *Streptomyces* spp. 053 | Cannae radices (*Canna indica*) The root of canna (*Canna indica*) | Reduce the concentrations of boron in the soil | Boron toxicity | |
| *Streptomyces* spp. AN090126 | Radices Nullam (Roots of Tomato) | Antifungal against *Ralstonia solanacearum* | Bacterial wilt, Moko disease of banana, brown rot of potato | [33] |
| *Streptomyces vinaceusdrappus* | Semotus an a agro rice (Isolated from the agricultural field of rice) | Antifungal activity against *Magnaporthe oryzae* (anamorph *Pyricularia oryzae*) | Rice blast | [39] |
| *Streptomyces* strain *CAI-21* | Semotus ab herbal vermicompost (Isolated from herbal vermicompost) | Antifungal activity against *Macrophomina phaseolina* | Charcoal-rot disease in sorghum | [59] |
| *Streptomyces lydicus WYEC108* | *S. lydicus WYEC108* condition cultura (*S. lydicus* WYEC108 stored culture) | Antifungal activity against *Pythium ultimum* | Seed blight or rot, damping off | |
| *Streptomyces violaceusniger YCED-9* | Systema radicum *Paraserianthes falcataria* (Root system of *Paraserianthes falcataria)* | Antifungal activity against *Pythium* and *Phytophthora* spp | Damping off, root rots of angiosperms | [60] |
| *Streptomyces spp. ACTA1557* | Rhizosphaerae solitariae cultus indigenarum plantarum in Graecia nascentium conditarum (Stored cultures isolated rhizospheres of indigenous plant growing in Greece) | antifungal activity against *Rhizoctonia solani* | Damping off | [61] |
| *Streptomyces spp. TM32* | Terrae rhizosphaericae ex agro turmericanae collectae (*Curcuma longa*) (Rhizospheric soils collected from the field of nurmeric *Curcuma longa*) | Antifungal activity against *Rigidoporus* spp. | White root | [62] |
| *Streptomyces goshikiensis YCXU* | Rhizosphaerium sano cucumbers (Rhizosphere of a healthy cucumber plant) | Antifungal activity against *Fusarium oxysporum f.* spp. *niveum* | *Fusarium* wilt | [63] |
| *Streptomyces* spp. *MR14* | Rhizospherium sinapis (Rhizosphere of the mustard plant) | Antifungal activity against *Pyricularia oryzae* | Rice blast disease | [64] |
| *Streptomyces* spp. *A20* | Rhizospheric terrae rice-coluerunt agros (Rhizospheric soils of rice cultivated fields) | Antibacterial activity against various bacteria | Bacterial Panicle Blight | [6] |
| *Streptomyces* spp. *5.1* | Rhizospheric terrae rice-coluerunt agros (Rhizospheric soils of rice cultivated fields) | Antibacterial activity against different bacteria | Bacterial panicle blight | [6] |
| *Streptomyces corchorusii* strain *UCR3-16* | Rice rhizospheric terrae (Rice rhizospheric soils) | Antifungal activity against *Rhizoctonia solani* | Damping off, stem lesions, stem rot, root rot | [65] |
| *Streptomyces* spp. CACIS-1.5CA | Puram culturam consecutus est a Germplasmo Bank of *Actinomycetes* (Pure culture obtained from the Germplasm Bank of *Actinomycetes*) | Antifungal activity | Tropical fruit rot | [66] |

the secretion of the volatile compound. For instance, the signal that *Streptomyces* strains receive determines which volatile compounds are secreted.

When a pathogen attaches to *Streptomyces* or a nutrient is deleted, -butyrolactones are released that assist *Streptomyces* in cell-cell communication.

## 7. COMPETITION FOR NUTRIENTS

It was discovered that the inoculum of certain *Streptomyces* species could improve the capacity for nitrogen fixation. For instance, *Streptomyces chartreusis* increased nitrogen fixation in sugarcane by up to 9.16%. However, it was found that the most effective sources of carbon and nitrogen for *Streptomyces* growth were mannitol and asparagine. Nevertheless, it was discovered that the presence of volatile compounds controls the competition between unrelated species. In addition, it is well known that alarm one ppGpp is crucial for producing antibiotics under nutritional deficiency conditions.

In addition, it was discovered that *Streptomyces*, as opposed to other bacterial species, could convert an insoluble phosphorous compound into its soluble form, allowing the plant to use it for assimilation. In addition, it shows that *Streptomyces spiralis* and *Micromonospora chalcea* were found to be efficient against *Fusarium oxysporum*, which is present in banana leaflets, and *Streptomyces* they showed a significant tendency to increase the production of IAA, which defines *Streptomyces*' capability to work with other species effectively [38].

## 8. *STREPTOMYCES* AS BIO-REMEDIATORS

*Streptomyces* were found to be effective during the bioremediation of organochlorine compounds, heavy metals, and hydrocarbons. Regarding *Streptomyces*, two essential processes of bioremediation have been identified, which include biologically controlled mineralization along with biologically induced mineralization (BIM). *Streptomyces* spp. 048 was found to form structural exopolymer substances (EPS) to remove boron. Further, *Streptomyces* spp. 053 was found to use the BIM mechanism to deal with the high boric acid concentration within the medium. According to Buzón-Durán *et al*. [39]. *Streptomyces*' capability to produce siderophore and *Streptomyces* EPS proved to be the reason for their effectiveness as bioremediation. For example, *Streptomyces* MC1 was found to have the property to reduce Cr (VI) into Cr (III) during the presence of 96% glycerol [39]. Similarly, *Streptomyces roseorubens SY and S. coelicolor A3(2)* absorb nickel (II) while the strain of *S. coelicolor A3(2)* was also found to remove copper (Cu(II)) from the medium [39].

## 9. PHYTOREMEDIATION

The removal of excessive concentrations of toxic heavy metals that build up in the soil due to natural and anthropogenic processes is done through phytoremediation, an environmentally friendly method [40]. These metals cannot biodegrade, so when they enter the food chain through plants, they seriously harm the ecosystem and human health. Decontaminating heavy metal-polluted soils improved plant growth, protection against pathogens, and heavy metal tolerance [40]. The process of extracting and detoxifying heavy metal contaminants from soils with the assistance of specific plants and the associated microbes is known as microbes-assisted phytoremediation [40]. Figure 2 outlines the different types of phytotoxins produced, their chemical nature and contributions to phytoremediation.

The soil microenvironment is improved by the ability of *Streptomyces pactum* and other *Streptomyces* spp. to facilitate the extraction of inorganic pollutants from the soil and their uptake by organisms [41,42]. This process enhanced chlorophyll and soluble protein contents, the antioxidant activities of superoxide dismutase and peroxidases and plant biomass of potherb mustard (*Brassica juncea*, Coss) growing in contaminated soil [41].

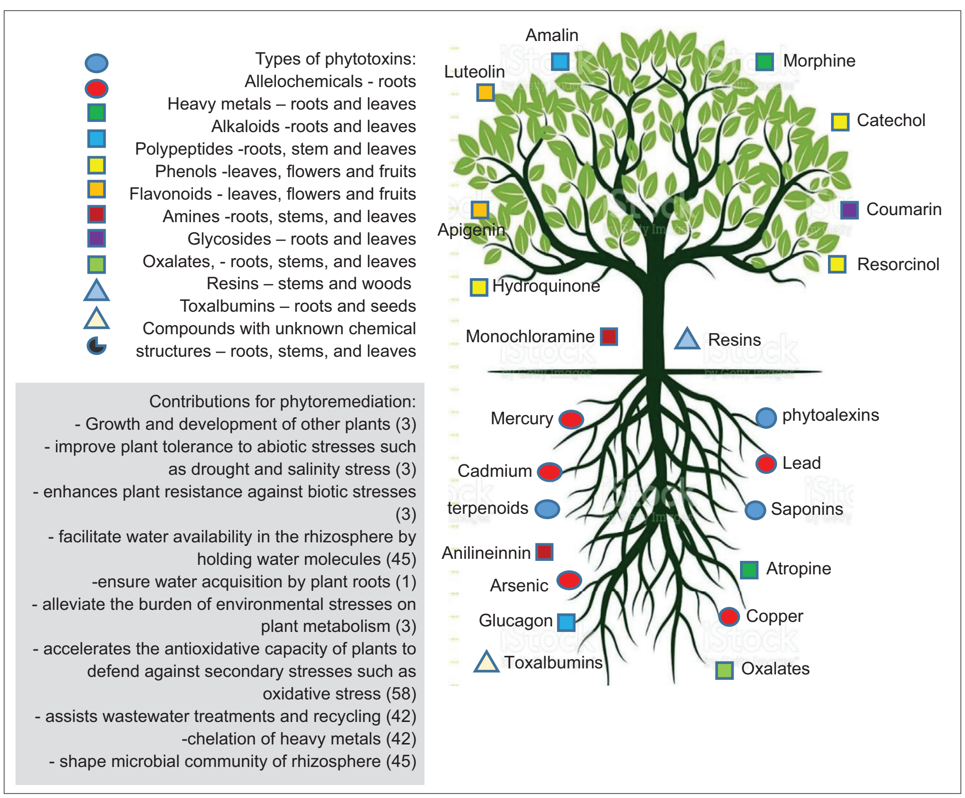


**Figure 2:** Different phytotoxins, their effects on plant organs, and their contribution to the phytoremediation. Different phytotoxins are illustrated with different colors. The site of action (roots, stems, or leaves) is also displayed.

**Table 3:** Percentage of increment in yield of different plants on inoculation *with Streptomyces* spp.

| ***Streptomycin* spp.** | **Host plant** | **% Increase** | **Reference** |
|---|---|---|---|
| *Streptomyces hydrogenans* strain DH-16 | *Solanum lycopersicum* (Tomato) | 23–30.2% increase in plant biomass | [67] |
| *Streptomyces lydicus* M01 | *Cucumis sativus* (cucumber) | 49.74% increase in yield | [68] |
| *Streptomyces palmae* PC 12 | *Oryza sativa* (rice) | 50% increase in biomass | [30] |
| *Streptomyces griseus* (CAI-24, CAI-121 and CAI-127) | *Cicer arietinum* (chickpea) | 23–37% increase in plant organs biomass | [69] |
| *Streptomyces roseocinereus* MS1B15 | *Hordeum vulgare* (barley) | 1.5% increase in shoot biomass | [70] |
| *Streptomyces shenzhenesis* TKSC3 | *Oryza sativa* (rice) | 33% increase in dry mass | [71] |
| *Streptomyces albus* | *Panicum miliaceum* (millet) | 9–12% increase in plant yield | [72] |
| *Streptomyces globisporus* | *Gossypium herbaceum* (cotton) | 62% increase in shoot biomass | [73] |
| *Streptomyces* spp. CLV45 | *Glycine max* (soybean) | 37% increase in shoot growth | [74] |
| *Streptomyces hydrogenans* DH16 | *Pisum sativum* (pea) | 39.45–58.04% increase recorded for numerous growth parameters | [11] |
| *Streptomyces* spp. JR9 | *Oryza sativa* (rice) | 18% increase in shoot biomass | [75] |
| *Streptomyces alfalfae* | *Panicum virgatum* (switchgrass) | 50% increase in shoot biomass | [76] |

## 10. FIELD TRIALS WITH *STREPTOMYCES*

The number of field trials highlighting the use of *Streptomyces* species for enhancing plant growth traits and biocontrol activities is constantly rising [43]. The percentage of increment in yield of different plants upon inoculation with *Streptomyces* spp. was given in Table 3.

For instance, a field experiment found that *Plasmodiophora brassicae*-caused Clubroot disease symptoms could be reduced when *S. alfalfae* XY25T was used as a biocontrol agent [43]. The study's findings showed that *S. alfalfae* XY25T had a high control efficiency of clubroot at 69.4% [43]. *S. alfalfae* XY25T reduced soil acidification by acting as a biocontrol agent [43]. In addition, it increased soil organic matter and made nitrogen available for plant processes. The soil's levels of other nutrients such as phosphorus and potassium and soil-organic content-enriching enzymes such as invertase, urease, catalase, and alkaline phosphatase increased [43].

*S. violaceusniger* controls the common scab disease of potatoes through the production of siderophores and improved potato crop yield by up to 26.8% due to its ability to produce phytohormones such as gibberellic acids and indole-3-acetic acid, fix nitrogen, and solubilize phosphate.

Most species of *Streptomyces* are involved in promoting plant growth, but some species, such as *Streptomyces scabiei* and *Streptomyces acidiscabies*, are pathogenic to plants [44]. Some *Streptomyces* species, like *S. filipinensis*, induce more IAA than others, like *S. atrovirens*. *S. spiralis* was used in an experiment on cucumbers. It was found to increase growth promotion and produce a comparatively higher yield of cucumbers when combined with related microbial activators such as *M. chalcea* or *Actinoplanes campanulatus* [45]. In addition, it was mentioned that using a consortium of these bacterial species reduced diseases such as seedling damping off and crown rot [45].

The previous research suggests a strong relationship exists between the plant species, the community in which it is found, and the *Streptomyces* species present in the rhizosphere to support plant growth [46]. In addition, it was hypothesized that altering the native species in a plant's environment would impact the antagonistic behavior of various *Streptomyces* [46]. For instance, a study used four distinct plant species: *Andropogon gerardii*, *Schizachyrium scoparium*, *Lespedeza capitata*, and *Lupinus perennis*, to highlight the reduced susceptibility of *A. gerardii* to the plant pathogens when grown in monoculture of *Streptomyces* species [47].

However, cultivating these plants in species-rich environments may reveal variations in the rhizosphere microbes' abilities to reduce pathogenicity and promote plant growth [48]. This feature demonstrates that *Streptomyces* species functions effectively when surrounded by a supportive plant community [49].

## 11. CONCLUSION

From the preceding, it can be inferred that *Streptomyces* spp. is highly effective at promoting plant growth because it has been discovered that it participates actively in several metabolic pathways that control plant growth, including the TAM and IAA pathways. The study above showed that *Streptomyces* produces phytohormones such as auxins, gibberellins, and cytokinin, which are essential for enhancing plant growth and yield. In addition, these microbes help plants fix nitrogen, scavenge ferric ions from the environment using siderophores, and lessen plant stress by producing 1-aminocyclopropane-1-carboxylate, which inhibits deaminase activity (ACC). Furthermore, it is essential to recognize *Streptomyces* species' role in reducing oxidative stress by detoxifying reactive oxygen species. Plants can fight off a wide range of pathogens thanks to their metabolism, which produces inhibitory allelochemicals and induces systemic resistance in various host plants. However, *Streptomyces* spp. are well known as an environmentally friendly solution for continuously expanding global problems due to their low pathogenicity and tolerance to harsh environmental conditions. These microbes enable the remediation of harmed soils by processing various secondary metabolites. Thus, plant-associated bacteria as plant growth stimulators can enhance the soil's health. This benefit is greatly needed in an era when many agrochemicals have been introduced and accumulated in the soil to increase crop productivity.

## 12. FUTURE PERSPECTIVES

Despite the many advantages that *Streptomyces* have for humans, it has been discovered that the presence of other organisms impacts their communities and, consequently, their abilities to promote growth. Therefore, examining *Streptomyces*' effectiveness in the presence of various organisms, such as endophytic and exophytic fungi, is necessary to highlight its role as a species that promotes plant growth in the future. A review of the performance of the growth-stimulating *Streptomyces* species in the presence of free-living rhizobacteria and bacteria associated with plant roots will also reveal more effective bacterial combinations that can be used to increase crop yields.

To sustain agriculture in the future, data mining on interactions between *Streptomyces* species and plants may produce new insights on plant growth-promoting agents. To effectively address issues like world hunger, thorough studies on the potential of *Streptomyces* species to benefit their biotic and abiotic environments are essential.

## 13. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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## 15. CONFLICT OF INTEREST

The author declares that they have no conflicts of interest.

## 16. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

## 17. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

## 18. PUBLISHER'S NOTE

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