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REVIEW

Actinomycetes: an unexplored microorganisms for plant growth promotion and biocontrol in vegetable crops

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Abstract

Actinomycetes, a Gram positive bacteria, well reported as a source of antibiotics, also possess potential to control various plant pathogens, besides acting as plant growth promoting agent. Chemicals in different forms are extensively being used in vegetable farming, adversely affecting the environment and consumer health. Microbial agent like actinomycetes can substantially replace these harmful chemicals, and have now started finding a place as an important input in to farming practices. Only selected vegetable crops belonging to 11 different families have been explored with use of actinomycetes as biocontrol and plant growth promoting agent till now. It provides ample opportunities to vegetable researchers, to further explore with use of this very important group of microorganisms, in order to achieve even higher production level of safe vegetables. Mycostop and Actinovate are two actinomycetes based formulations globally available for use in vegetable farming as a substitute for chemical formulations. Present review article has summarized the literature available on use of actinomycetes in vegetable farming. Existing wide gap in knowledge, and potential thrust areas for future research have also been projected.

Keywords Actinomycetes · Biocontrol · Plant growth promotion · Vegetable

Abbreviations

ACC	1-Aminocyclopropane-1-carboxylate
IAA	Indole actetic acid
MPPF	Mycelia preparation of pathogenic fungi
PGP	Plant growth promotion
DAT	Day after transplantation
CFU	Colony forming unit
RHB	Rhizobia helper bacteria
KI	Kinetin

Introduction

Actinomycetes, a Gram positive bacteria, and a major source of most of the antibiotics being used, are also being explored as plant growth promoting and biocontrol agent for various crop plants. Either the organism itself as bio-formulation or metabolites isolated from it, and/or its derivatives are being used for this purposes. When compared with other groups of microorganism, actinomycetes are relatively less explored with agricultural perspective in general and vegetable in particular. Though vegetable crops play a major role in achieving nutritional security in developing country like India, apart from enhancing the per capita income of the farmers, usually have problems of disease, insect, and pest. To control it, and to enhance vegetables productivity chemicals in form of fertilizer, pesticide, and herbicide are being used extensively, which have led to several concerns regarding environment and human health including ever increasing cost of production, besides affecting vegetables export business potential in international market (PIB 2015; Sinha et al. 2012). To overcome these problems, several eco-friendly approaches including various biological formulations have been developed and being used to replace or used in combination of these chemicals. Among the 18 major lineages recognized in bacterial domain as per Bergey's Manual of Systematic Bacteriology (Whitman et al. 2012), actinomycetes also known as actinobacteria is one of the largest taxonomic unit comprising of five subclases, six orders, and 14 suborders (Ludwig et al. 2012). Among different genera *Streptomyces* is extensively researched one as it is comparatively easy to isolate. Genera difficult to isolate were termed as non streptomyces actinomycetes or rare actinomycetes. With the discovery of more and more specific media, researchers have now revealed that rare actinomycetes are not in fact rare, but

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as widely available as *Streptomyces* genus. This group of microorganisms is also a source of bio-active metabolites, and can degrade a wide range of recalcitrant compounds, so has been recommended as a best bio-degrader (Pizzul et al. 2006; Eshelli et al. 2015). They can degrade different types of pesticide (Lin et al. 2011; Fuentes et al. 2004), herbicide (Esposito et al. 1998; Arya et al. 2016), insecticide (Polti et al. 2014), besides acting as biopesticide and bioherbicide agent (Zhang et al. 1998; Danasekaran et al. 2010; De Schrijver and De Mot 1999). Actinomycetes strains have also been developed as eukaryotic expression vector for bulk production of eukaryotic proteins (Nakashima et al. 2005). Though many reviews are available on different aspects of actinomycetes like as a source of novel bio-active compounds and natural products, as a storehouse and discovery of next generation of antibiotics (Barka et al. 2016; Matsumoto and Takahashi 2017; Jose and Jha 2016; Genilloud 2017; Dinesh et al. 2017; Genilloud et al. 2011), and as biocontrol and plant growth promoting agent in general (Vurukonda et al. 2018), but information on use of actinomycetes as biocontrol and plant growth promoting agent particularly for vegetable crops is by and large not available at one place. Keeping these literature constrains in view and for the benefit of vegetable researchers effort has been made to review and compile information pertaining to use of actinomycetes for plant growth promotion and biocontrol in vegetable crops.

Actinomycetes as biocontrol and plant growth promoting agent for vegetable crops

Solanaceous vegetables

Researchers have mainly focused on tomato and chilli while exploring actinomycetes applicability for solanaceous vegetables (Table 1). Endophytic *Streptomycetes* strain S30 isolated from surface sterilized tomato root interior promoted growth along with enhanced resistance to *R. solani* in tomato but not so in cucumber seedlings (Cao et al. 2004). Furthermore endophytic *Streptomycetes* spp. isolated from healthy tomato root was also reported to act as biocontrol agent against *Ralstonia solanacearum* causing wilt of tomato under in vitro condition (Tan et al. 2006), and also for both plant growth promotion and management of tomato bacterial wilt under *in-vivo* condition too (Sreeja and Gopal 2013). In contrast endophytic *Streptomycetes* strain DHV3-2 isolated from root of diseased tomato plant showed potent biocontrol effect against *Verticillium dahliae* under both *in-vitro* and *in-vivo* condition besides enhancing plant growth (Cao et al. 2016). Therefore it is recommended that researchers should target both healthy and diseased plants while searching for potent endophytic actinomycetes strain. Endophytic actinomycetes belonging to both streptomycetes and non-streptomycetes genera isolated from roots of healthy native plants *Aristida pungens, Cleome arabica, Solanum nigrum, Panicum turgidum, Astragallus armatus, Peganum harmala, Hammada scoparia* and *Euphorbia helioscopia* of Algerian Sahara region were evaluated for their biocontrol potential against *Rhizoctonia solani* damping-off and plant growth promoting traits. Two strains CA-2 (*Streptomyces mutabilis* NBRC 12800T) and AA-2 (*Streptomyces cyaneofuscatus* JCM 4364T) reduced the disease incidence which was comparable to thioperoxydicarbonic diamide tetramethylthiram (TMTD) treatment besides increasing fresh weight, seedling and root length of tomato (Goudjal et al. 2014). Earlier they have also isolated endophytic actinomycetes from five different herbaceous plants (*Cleome arabica, Solanum nigrum, Astragallus armatus, Aristida pungens* and *Panicum turgidum*) collected from Hassi R'mel region of Algerian Sahara, and evaluated for indole-3-acetic acid (IAA) production. Tomato seeds treated with culture supernatant of *Streptomycetes* sp. PT2 strain [isolated from *Panicum turgidum*] containing crude IAA [100.03 ± 0.34 µg/ml] promoted seed germination and root elongation (Goudjal et al. 2013). Endophytic *Micromonospora* spp. isolated from tomato inhibited *Fusarium oxysporum* f. *lycopersici* (Smith 1957). *Micromonospora* spp. isolated from surface sterilized nodules of healthy alfalfa leguminous plant minimized pathogenic fungi *Botrytis cinerea* leaf infection when inoculated in tomato root. Jasmonates led induced systemic resistance played a key role in defense process as JA-deficient tomato line def1 did not show long term induced resistance by *Micromonospora* inoculation. These strains can be used both for priming the plant immunity and also as antifungal agent against plant pathogens (Martinez-Hidalgo et al. 2015). Thus potent actinomycetes strain obtained from one plant can also be applied to inhibit pathogen of another plant. Usually potent actinomycetes strain inhibits particular pathogen infecting many different crops, possible because their mode of action remain same. But same strain may also inhibits different pathogens affecting different crops due to its broad spectrum of activity as reported by Kunova et al. (2016), and elaborated subsequently. *Streptomyces vinaceus* strain St24 isolated from root-stem junction of tomato plant was reported with acaricidal activity, and on foliar spray protected tomato plants against *Botrytis cinerea* causing gray mold disease (Wang et al. 2012). *Streptomyces* sp. strain DBT204 isolated from tomato showed plant growth promoting traits in seedlings of both chilli and tomato. Genes *iaaM* and *acdS* were amplified, phytohormones like indole acetic acid, kinetin, and six antibiotics were detected and quantified (Passari et al. 2016). They have also reported endophytic *Streptomyces* sp. strain BPSAC 34 and *Leifsonia xyli* strain BPSAC 24 isolated from ethanomedicinal plants of Mizoram India which led to maximum increase in shoot and

Table 1 Actinomycetes application in Solanaceous vegetables

Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
Chilli (*Capsicum annuum* L.)	Medicinal plants	*Streptomyces* sp. (BPSAC34) *Leifsonia xyli* (BPSAC24)	PGP and biocontrol	Plant-pathogens, i.e. *Rhizoctonia solani* (MTCC-9666), *Fusarium graminearum* (MTCC-1893) and *Fusarium oxysporum* (MTCC-284)	Passari et al. (2015)
Capsicum annuum L.	Rhizospheric soil	Actinomycetes strains OUA3, OUA5, OUA18, and OUA40	Biocontrol	*Colletotrichum capsici* and *Fusarium oxysporum*	Ashokvardhan et al. (2014)
Chilli	Probiotic bacteria	*Actinomycetes* sp. (ATS6)	Biocontrol, Improve chilli seed quality/prevent seed borne disease	*Colletotrichum acutatum*	Tefa et al. (2015)
Chilli	Rhizospheric soil	*Actinomycetes* PACCH 277, PACCH129, PACCH225, PACCH24 and PACCH246, *Streptomyces hygroscopicus*	Biocontrol and PGP, control stem rot diseases	*Sclerotium rolfsii*	Pattanapipitpaisal and Kamlandharn (2012)
Chilli	Chilli rhizosphere	*Streptomycetes indiaensis* KJ872546	Wilt causing fungal pathogen i.e. *Fusarium oxysporum*	*Fusarium oxysporum*	Jalaluldeen et al. (2014)
Chilli	Culture collection of Chiang Mai University, Thiland	*Streptomyces* sp.	Biocontrol	*Fusarium oxysporum* f.sp. *capsici* isolate FoC4	Saengnak et al. (2013)
Red Chilli	Soil samples	*Streptomycetes ambofaciens* S2	Biocontrol, causal agent for anthracnose	*Colletotrichum gloeosporioides*	Heng et al. (2015)
Chilli pepper	Antibiotic derived from *Streptomyces* sp. AG-P 1441 (AG-P 1441)	Paromomycin, antibiotic derived from *Streptomyces* sp. AG-P 1441 (AG-P 1441)	Phytophthora blight and soft rot diseases	*Phytophthora capsici* and *Pectobacterium carotovorum*	Balaraju et al. (2016)
Red peppers	Soil	*Streptomyces halstedii* AJ-7	Biocontrol of phytophthora blight in red-peppers	*Phytophthora capsici*	Joo (2005)
Tomato	Endophytic	*Streptomyces* sp.	Bacterial wilt in tomato	*Ralstonia solanacearum*	Sreeja and Gopal (2013)
Tomato	Rhizospheric soil	*Streptomycetes* sp.	PGP by producing ACC deaminase, IAA	–	El-Tarabily (2008)
Tomato	Roots of healthy native plants of Algerian Sahara	*Streptomyces* sp.	PGP and biocontrol	*Rhizoctonia solani* damping-off of tomato seedlings	Goudjal et al. (2014)
Tomato	Endophytes from root	*Streptomyces* sp.	promoted growth and enhanced resistance to *R. solani* in tomato seedlings	*Rhizoctonia solani*	Cao et al. (2004)
Tomato	Endophytes from root	*Streptomyces* sp.	Biocontrol	*Ralstonia solanacearum*	Tan et al. (2006)
Tomato	Endophytes from herbaceous plants (*Cleome arabica, Solanum nigrum, Astragallus armatus, Aristida pungens* and *Panicum turgidum*)	*Streptomyces* sp.	PGP through IAA, promoting seed germination and root elongation	–	Goudjal et al. (2013)
Tomato	Endophytes	*Micromonospora* sp.	Wilt	*Fusarium oxysporum* f. *lycopersici*	Smith (1957)

Table 1 (continued)

Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
Tomato	Nodules of alfalfa	*Micromonospora* sp.	Control fungal pathogen and stimulate plant immunity	Leaf infection by *Botrytis cinerea*	Martínez-Hidalgo et al. (2015)
Tomato	diverse Greek habitats/Rhizospheric soil	*Streptomyces rochei* ACTA1551	protect tomato seeds from *F. oxysporum* infection in vivo, promote the growth of tomato plants when the pathogen was absent	*Fusarium oxysporum* f.sp. *lycopersici*	Kanini et al. (2013)
Tomato	Polyene antibiotics strevertene A strevertene B from culture exrtact of *S. psammoticus*	*Streptomyces psammoticus* strain KP1404	Fusarium wilt of tomato	*Alternaria mali, Aspergillus oryzae, Cylindrocarpon destructans, Colletotrichum orbiculare, Fusarium oxysporum* f.sp. *lycopersici* and *Sclerotinia sclerotiorum*	Kim et al. (2011)
Tomato	Endophytes from root of diseased tomato plant	*Streptomyces* sp. strain DHV3-2	biocontrol of fungal diseases caused by *Verticillium dahliae* and PGP	*Verticillium dahliae*	Cao et al. (2016)
Tomato	root-stem junction of tomato plant	*Streptomyces vinaceus* St24	Biocontrol of gray mold disease	*Botrytis cinerea*	Wang et al. (2012)
Tomato	Culture collection	*Bacillus thuringiensis* CR-371, *Streptomyces avermectinius* NBRC14893	Bacterial wilt, root-knot nematod	Soilborne pathogens *Ralstonia solanacearum, Meloidogyne incognita*	Elsharkawy et al. (2015)
Tomato	Culture collection	*Saccharothrix algeriensis* NRRL B-24137	Tomato wilt	*Fusarium oxysporum* f.sp. *lycopersici* (FOLy)	Merrouche et al. (2017)
Tomato, Chilli	Termites	*Streptomyces rubrolavendulae* S4	Biocontrol	*Phytophthora infestans*, causing damping off disease in nurseries	Loliam et al. (2012)
Tomato, Chilli	Endophytes from tomato	*Streptomyces* sp. strain DBT204	PGP [phytohormones IAA, KI]	–	Passari et al. (2016)
Cultivated rocket, Lamb, Lettuce and Tomato	Endophytic *Streptomycetes* spp. available at Culture Collection, Università degli Studi di Milano, Italy	*S. cyaneus* ZEA17I, *S. anulatus* CMJ58I and *S. albidoflavus* VT111I	Biocontrol and/or PGP	Soil borne fungal pathogens *Sclerotinia sclerotiorum* FW361, *Rhizoctonia solani* FW408, *Fusarium oxysporum* f.sp. *lactucae* L74, *Pythium ultimum* FW407, *Phytophthora* sp. FW409 and *Thielaviopsis basicola* FW406	Kunova et al. (2016)

root length of chilli plant when used as a mixture (Passari et al. 2015). Endophytic *Streptomycetes* strains *S. cyaneus* ZEA17I, *S. anulatus* CMJ58I and *S. albidoflavus* VT111I, [from microbial collection of Department of Food, Environmental and Nutritional Sciences (DeFENS), University of Milan, Italy] showed broad-spectrum to specific inhibition against six soil borne pathogens *Sclerotinia sclerotiorum* FW361, *Rhizoctonia solani* FW408, *Fusarium oxysporum* f.sp. *lactucae* L74, *Pythium ultimum* FW407, *Phytophthora* sp. FW409 and *Thielaviopsis basicola* FW406. These strains were used to colonize seeds of vegetable crops like tomato, cultivated rocket, lamb lettuce, and lettuce. In vitro experiment showed improved radical and hypocotyl growth in tomato seedlings. Occasional negative influence on plant growth was overcome during further development of plant (Kunova et al. 2016).

Rhizosphere competent 1-aminocyclopropane-1-carboxylic acid deaminase- producing *Streptomycetes filipinensis* no.15 and *S. atrovirens* no.26 strains isolated from tomato rhizospheric soil exhibited plant growth promoting traits. *Streptomycetes filipinensis* no.15 was superior in PGP performance on tomato compared with *S. atrovirens* no.26, as it also produced IAA along with ACC deaminase activity which enhanced plant growth by reducing endogenous ethylene through in planta ACC (El-Tarabily 2008). *Streptomyces rochei* ACTA1551, isolated from rhizospheric soil of plant *Pinus brutia* of Greek, protected tomato seeds from *Fusarium oxysporum* f.sp. *lycopersici* infection in vivo, and promoted tomato plant growth in absence of pathogen (Kanini et al. 2013). Strevertenes A and B isolated from culture extract of *Streptomyces psammoticus* strain KP1404 retarded Fusarium wilt development on tomato comparable to that of benomyl (Kim et al. 2011). Bacterial wilt and root-knot nematode was suppressed when tomato root was treated with both *Bacillus thuringiensis* CR-371 and *Stremptomyces avermectinius* NBRC 14893 strains (Elsharkawy et al. 2015). Soil pretreatment with actinobacteria *Saccharothrix algeriensis* NRRL B-24137 (SA) significantly reduced tomato wilt caused by *F. oxysporum* f.sp. *lycopersici* (Merrouche et al. 2017). Colonization of tomato and chili seedlings with *Streptomyces rubrolavendulae* S4 strain isolated from termite mounds considerably increased seedlings survival in *Phytophthora infestans* contaminated peat moss, comparable to fungicide metalaxyl, and as such has been recommended against damping off disease in tomato and chili nursery (Loliam et al. 2012).

Actinomycetes strains isolated from chilli rhizospheric soils manifested antifungal activity against *Colletotrichum capsici* and *Fusarium oxysporum* along with production of chitinases and other hydrolytic enzymes emphasizing their use as biocontrol agent (Ashokvardhan et al. 2014). Chilli seeds coated with probiotic bacteria including actinomycetes exhibited antagonistic activity against *Colletotrichum acutatum* to prevent seed borne diseases besides increasing seed viability (Tefa et al. 2015). Actinomycetes strain PACCH24 (*Streptomyces hygroscopicus*) inhibited *Sclerotium rolfsii*, and showed biocontrol activity on chilli seedlings, and can be used to control stem rot disease and for better growth of chilli (Pattanapipitpaisal and Kamlandharn 2012). *Streptomycetes indiaensis* strain KJ872546 isolated from chilli rhizospheric soil was reported to be antagonistic against wilt pathogen *(Fusarium oxysporum)* as it produces hydrogen cyanide, volatile and diffusible antifungal metabolites, and ammonia (Jalaluldeen et al. 2014). *Streptomyces* spp. strain NSP4 from culture collection of Chiang Mai University, Thiland reduced Fusarium wilt disease (*Fusarium oxysporum* f.sp. *capsici* isolate FoC4) in green house (Saengnak et al. 2013). *Streptomyces ambofaciens* strain S2 was reported effective against *Colletotrichum gloeosporioides*, causing anthracnose disease in red chilli fruits, and showed no sign of infection when its ethyl acetate extract was sprayed on chilli fruit. (Heng et al. 2015). Chili peeper plants treated with aminoglycoside paromomycin, derived from *Streptomyces* sp. AG-P 1441 (AG-P 1441) controlled *Phytophthora* blight and soft rot diseases caused by *Phytophthora capsici* and *Pectobacterium carotovorum* respectively (Balaraju et al. 2016). Red-pepper seeds soaked in culture broth of soil isolate *Streptomyces halstedii* strain AJ-7 reduced growth of soil inoculated *Phytophthora capsici* causing *Phytophthora* blight in red-pepper (Joo 2005). Only two actinomycetes genera (*Streptomyces* and *Micromonospora*) have been used for solanaceous vegetables till date, leaving much scope for researchers to explore with majority of left out genera of this group of microorganisms. While on other side potato and eggplant belonging to vegetable genera *Solanum* of this family, Indian nightshade (*Solanum indicum*), ground cherry (*Physalis pubescens*), and many other cultivated solanaceous vegetables still need researchers attention from actinomycetes applicability point of view.

Cucurbitaceous vegetable crops

Cucumber and melon are two major cucurbitaceous vegetable have been explored with actinomycetes application (Table 2). Glucanase producing three cucumber root endophytic actinomycetes i.e. *Actinoplanes campanulatus, Micromonospora chalcea, Streptomyces spiralis* when applied in combination were found as effective as metalaxyl a recommended fungicide for Pythium disease. These actinomycetes strains successfully reduced damping-off, and crown and root rot of cucumber by suppressing pathogenic activities of *P. aphanidermatum* on seedling and mature cucumber plant besides promoting plant growth (El-Tarabilyet et al. 2009). Rhizosphere competent non-streptomycete actinomycetes (*Actinoplanes philippinensis* Couch, *Microbispora rosea* Nonomura and Ohara, *Micromonospora*

Table 2 Actinomycetes application in Cucurbitaceous vegetables

Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
Cucumber	Root	*Actinoplanes campanulatus, Micromonospora chalcea, Streptomyces spiralis*	PGP and biocontrol	*Pythium aphanidermatum*	El-Tarabily et al. (2009)
Cucumber	Cucumber phyllosphere	*Actinomycete* XN-1	Biocontrol	*Corynespora cassiicola*	Wang and Ma (2010–2011)
Cucumber	Rhizospheric soil	*Streptomyces* sp.	Biocontrol	Root pathogen *Pythium aphanidermatum*	Postma et al. (2005)
Cucumber	Cucumber rhizosphere soil	*Actinoplanes philippinensis* Couch, *Microbispora rosea* Nonomura and Ohara, *Micromonospora chalcea*	Post emergence damping-off of cucumber	*Pythium aphanidermatum*	El-Tarabily (2006)
Cucumber	From various habitats in China	*Streptomyces rimosus*	Fusarium wilt of cucumber, biocontrol and PGP	*Fusarium oxysporum* f.sp. *cucumerinum*	Lu et al. (2016)
Cucumber	Soil	*Streptomyces bikiniensis* HD-087	Cucumber Fusarium Wilt	*Fusarium oxysporum* f.sp. *cucumerinum*	Zhao et al. (2012)
Cucumber	Endophytes from medicinal plant *Alisma orientale*	Bioactive compound staurosporine from strain CNS-42	PGP and biocontrol	*F. oxysporum* f.sp. *cucumerinum*	Li et al. (2014)
Cucumber	Soil and compost	*Paenibacillus* sp. 300 and *Streptomyces* sp. 385	Fusarium wilt of cucumber (*Cucumis sativus*) caused by *Fusarium oxysporum* f.sp. *cucumerinum*	*Fusarium oxysporum* f.sp. *cucumerinum*	Singh et al. (1999)
Cucumber	Culture collection	*Streptomyces albospinus* CT205 alone or combined with organic fertiliser (BOF-CT205)	Cucumber Fusarium wilt	*Fusarium oxysporum*	Wang et al. (2016)
Cucumber	Endophytes from cucumber (*Cucumis sativus*) and pumpkin (*Cucurbita moschata*)	*Streptomycetes* sp. MBCu-56	Cucumber anthracnose	*Colletotrichum orbiculare*	Masafumi et al. (2009)
Cucurbits	Soil	*Streptomyces* sp.	Biocontrol	Cucurbit plant pathogens *Fusarium* sp./*Alternaria* sp.	Zhao et al. (2013)
Cucumber	Soil samples	*Actinoplanes* sp. HBDN08 Antifungal compound-5-hydroxyl-5-methyl-2-hexenoic acid	Antifungal activity	Cucumber-*B. cinerea* [cucumber gray mold (CGM)], *C. cucumerinum* [cucumber scab (CS)], *C. cassiicola* [cucumber target leaf spot (CTLS)]	Zhang et al. (2010)
Melons	Cucurbit fruits	Actinobacteria	Biocontrol	*Pseudomonas syringae* pv. *lachrymans*	Glassner et al. (2015)
Melon	Capsicum crop	*Streptomyces* sp.	Biocontrol	*Macrophomina phaseolina*	Etebarian (2006)

chalcea (Foulerton) Ørskov, and *Streptomyces griseoloalbus* (Kudrina) Pridham et al.) isolated from cucumber rhizospheric soil, and producing cell wall degrading enzymes, were found to suppress *Pythium aphanidermatum* causing damping-off of cucumber seedlings as comparable to metalaxyl (El-Tarabily 2006).

Actinomycete strain XN-1 isolated from cucumber phyllosphere is reported to inhibit the growth of *Corynespora cassiicola* causing cucumber target leaf spot in greenhouse (Wang and Ma 2010–2011). Filamentous actinomycetes isolated from unsterilized reused rockwool successfully suppressed *Pythium aphanidermatum* causing root rot in cucumber grown on rockwool (Postma et al. 2005). *Streptomyces rimosus* Strain M527 isolated from China, promoted cucumber shoot growth, and prevented wilt disease caused by *F. oxysporum* f.sp. *cucumerinum* with 72.1% control efficacy in cucumber seedlings when root was irrigated with broth of this strain (Lu et al. 2016). Similarly fermentation broth of *Streptomyces bikiniensis* strain HD-087 isolated from China grassland soil, effectively suppressed cucumber wilt caused by *F. oxysporum* f.sp. *cucumerinum* by inhibiting conidia germination and destroying its membrane, leading to cytoplasmic leakage and also triggered induced resistance through increase in enzymes like peroxidase, phenylalanine ammonia-lyase, and beta-1,3 glucanase activity in cucumber. (Zhao et al. 2012). While Singh PP et al. (1999) obtained best ($p < 0.05$) result when mixture of two chitinolytic bacterial strains *Paenibacillus* sp. 300 and *Streptomyces* sp. 385 were used in 1:1 or 4:1 ratio, and applied as zeolite using chitosan based media at the rate of 6 g/kg of potting medium 15 days before planting cucumber seeds. Hydrolytic enzymes like chitinase and beta-1,3-gluccanase were reported to play significant role in biocontrol process. Endophytic strain CNS-42 isolated from Chinese medicinal plant *Alisma orientale* showed largest zone of inhibition against soil borne pathogen *F. oxysporum* f.sp. *cucumerinum*, and significantly reduced ($p < 0.05$) disease severity index, and also increased fresh shoot weight and height of cucumber plantlets when treated with this strain. Staurosporine was reported to be responsible for its biocontrol activity, and it was also first time reported to be responsible for plant growth promoting activities (Li et al. 2014). *Streptomyces albospinus* CT205 in combination with organic fertilizer (BOF-CT205) significantly reduced Fusarium wilt incidence by reducing ca. 55%, besides enhancing cucumber yield to 8.3×104 kg/ha (Wang et al. 2016). Endophytic *Streptomyces* sp. MBCu-56 isolated from cucumber effectively controlled cucumber anthracnose caused by *Colletotrichum orbiculare* in seedlings (Masafumi et al. 2009). Intertwining and degradation of fungal hypha of different *Fusarium* sp. and *Alternaria* sp. were observed when antagonistic *Streptomyces* sp. were grown in media containing mycelia preparation of pathogenic fungi (MPPF) of cucurbit plants as soul carbon source because of enhanced production of extracellular enzymes like cellulase, chitinase, and glucanase (Zhao et al. 2013). Antifungal metabolite 5-hydroxyl-5-methyl-2-hexenoic acid isolated from *Actinoplanes* sp. HBDN08, a Chinese soil isolate, effectively controlled cucumber pathogens like *B. cinerea* [cucumber gray mold (CGM)], *C. cucumerinum* [cucumber scab (CS)], and *C. cassiicola* [cucumber target leaf spot (CTLS)] at 71.42%, 78.63% and 65.13% when applied at 350 mg/L in greenhouse experiment (Zhang et al. 2010).

Endophytic bacteria like Alpha, Beta, and Gammaproteobacteria, Firmicutes, Actinobacteria (*Streptomyces* spp.) isolated from mesocarp of *Cucumis melo* Reticulatus Group 'Dulce' fruit showed antimicrobial activity against major cucurbit pathogens like *Macrophomina phaseolina* (Mac), *Fusarium oxysporum* f.sp. *melonis* races 1 and 2 (FOM 1 and FOM 2, respectively), *F. oxysporum* f.sp. *radicis-cucumerinum* (Forc) and *Pseudomonas syringae* (P.s.). Furthermore these endophytes not only improved growth and protected plant in field but also showed promising post harvest effect by increasing fruit shelf life through delayed softening and spoilage (Glassner et al. 2015). *Streptomyces* strains A22, A20, A15, and STL obtained from glasshouse crop of capsicum inhibited growth of *Macrophomina phaseolina* causing charcoal stem rot of melon in soil and in seed treatment experiments (Etebarian 2006). Thus it is advisable that while searching for competent endophytic actinomycetes strain particularly for cucurbitaceous vegetable crops, besides root researchers should also target other plant parts like leaves and fruits. In consortium approach, compatibility of actinomycetes with other groups of microorganism, organic and/or chemical fertilizer should also be explored. So far only four genus of actinomycetes (*Streptomyces, Actinoplanes, Micromonospora*, and *Microbispora*) have been used just for two cucurbitaceous vegetables, leaving much scope to work with rest of actinomycetes genera for many left out important cucurbitaceous vegetables like bitter gourd, bottle gourd, pointed gourd, ash gourd, watermelon, pumpkin and squashes.

Brassicaceae or Cruciferous vegetables

Cabbage, radish, cauliflower, and lettuce are major cruciferous vegetable crops researched with actinomycetes application (Table 3). Cabbage endophytic strain MBCN152-1 identified as *Streptomyces humidus* controlled damping-off disease caused by seed-borne *Alternaria brassicicola* when artificially pathogen infested cabbage seeds were sown in 1.5×10^7 MBCN152-1 spores per gram of soil mix in green house experiment (Hassan et al. 2017). Lee et al. (2008) also isolated endophytic actinomycetes identified as *Microbispora rosea* subsp. *rosea* (strain A004 and A011) and *Streptomyces*

Table 3 Application of actinomycetes in Brassicaceae or Cruciferous vegetables

	Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
1.	Cabbage	Endophytes from cabbage	Strain MBCN152-1 -identified as a *Streptomyces humidus*-related species	Biocontrol	*Alternaria brassicicola*	Hassan et al. (2017)
2.	Chinese cabbage	Root	*Microbispora, Streptomyces, Micromonospora*	Biocontrol	*Plasmodiophora brassicae*	Lee et al. (2008)
3.	Cabbage seeds	Culture collection (culture filtrate of *S. padanus* strain PMS-702)	*Streptomyces padanus* strain PMS-702	Damping-off of cabbage	*Rhizoctonia solani* AG-4	Shih et al. (2003)
4.	Radish (*Raphanus sativus*)	Soil	*Streptomyces hydrogenans* DH16	Biocontrol of seed borne pathogens, and as spray to control black leaf spot of crucifers	*Alternaria brassicicola*, causal agent of black leaf spot and damping off of seedlings of crucifers	Manhas and Kaur (2016)
5.	Radish seedlings	Endophytes in cacao fruits and seeds	*Streptomyces violaceusniger* clade	PGP and Biocontrol	*P. megakaria* *P. erythroseptica* *F. oxysporum* *B. cinerea* *A. tumefaciens* *S. scabiei*	Tchinda et al. (2016)
6.	Cauliflower, cabbage, lettuce	Finnish Sphagnum peat	Mycostop (*Streptomycetes griseoviridis*)	Biocontrol of seedborne and soil borne fungal pathogens	*Alternaria brassicicola* on cauliflower and cabbage, and *Botrytis cinerea* on lettuce	White et al. (1990)

olivochromogenes (strain A018) from Chinese cabbage root which effectively suppressed clubroot disease caused by *Plasmodiophora brassicae*. Control value of 58% and 33% for strain A004 and A001, and 42% for A018 were reported when germinated Chinese cabbage seeds were inoculated with these actinomycetes strains, and transplanted to *P. brassicae* post inoculated pots. Cabbage seeds treatment with culture filtrate of *Streptomyces padanus* strain PMS-702 significantly reduced damping-off disease of cabbage by antagonizing the causative organism *Rhizoctonia solani* AG-4. This was the first report of polyene macrolide fungichromin acting as active ingredient from *S. padanus* filtrate controlling *Rhizoctonia* damping-off disease of cabbage (Shih et al. 2003). Endophytes belonging to *Streptomyces violaceusniger* clade isolated from cacao fruits and seeds showed plant growth promoting ability on radish seedlings inoculation (Tchinda et al. 2016). Several members of this clade are well reported as biocontrol agent, and as antibiotic geldanamycin producer. Soil isolate *Streptomyces hydrogenans* DH16 (GanBank:JX123130) and its metabolite significantly controlled *Alternaria brassicicola* causing black leaf spot seedlings damping off of crucifers. Damping off of *Raphanus sativus* seedlings were controlled, seed germination (75–80%) and vigor index (1167–1538) improved on dressing seeds by *S. hydrogenans* DH16 and its culture supernatant (10%). Manhas and Kaur (2016) concluded its application as biofungicide to control seed borne pathogens and black leaf spot of crucifers by seed dressing and spray respectively. *Alternaria brassicicola* on cauliflower and cabbage, and *Botrytis cinerea* on lettuce were controlled by *Streptomyces griseoviridis* isolated from Finnish Sphagnum peat (White et al. 1990). Only two genera (*Streptomyces, Microbispora*) of actinomycetes have been used for four cruciferous vegetables, giving plenty of opportunities to vegetable researchers for future research.

Amaranthaceae vegetables

Sugar beet (*Beta vulgaris*) is only vegetable crop of the Amarathaceae family which has been extensively researched for actinomycetes applicability (Table 4). Endophytic actinomycetes identified as *Streptomyces griseofuscus* and *Streptomyces globisporus* along with other bacterial and fungal strains isolated from root and leaves of healthy sugar beet cultivars showed plant growth promoting traits (Shi et al. 2009). In addition it was recommended to be applied to tissue culture plantlets at nursery stage before field transplantation for better establishment of endophytes. Errakhi et al. (2007) reported *Streptomyces* spp. strain J-2 isolated from Moroccan soils significantly decreased disease severity of *Sclerotium rolfsii* led damping-off disease in sugar beet besides significantly increasing seedlings development. Strain J-2 was selected after in-vitro screening experiment, and was used for sugar beet seeds treatment at 10^7–10^8 CFU/seed which led to 66% and 47% reduction in damping-off in non-sterilized and sterilized soil respectively. Higher percentage of pathogen reduction in non-sterilized soil indicate that other soil microbes either enhance the biocontrol process in consortia mode or through increased activity of *Streptomces* spp. J-2 strain itself which needs to be further researched. They further reported that inhibitor(s) obtained from culture filtrate of *Streptomyces* isolates J-2 and B-11 inhibited sclerotial germination 100%, and hyphal growth by 80% (Errakhi et al. 2009). Mixture of biomass and culture filtrate of these *Streptomyces* strains significantly reduced sugar beet root rot when being applied to *S. rolfsii* infested soil, and was recommended for integrated control of soil borne plant pathogens. So while looking for consortium approach researchers should not only confined to different microbial strains combinations, but should also take culture filtrate into consideration. Karimi et al. (2012) reported that native *Streptomyces* isolates (C and S2) on soil treatment (especially saline soil) inhibited root rot of sugar beet caused

Table 4 Application of actinomycetes in Amaranthaceae vegetables

Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
Sugar beet	Leaf and root	*Streptomyces griseofuscus, Streptomyces globisporus*	PGP	–	Shi et al. (2009)
Sugar beet	Moroccan soils	*Streptomycetes* sp.	Damping-off of sugar beet seeds	*Sclerotium rolfsii*	Errakhi et al. (2007)
Sugar beet	Native isolates	*Streptomyces* isolates (C and S2)	Biocontrol of root rot of sugar beet	*Rhizoctonia solani* AG-2, *Fusarium solani* and *Phytophthora drechsleri*	Karimi et al. (2012)
Sugar beet	Native isolates	*Streptomyces* sp.	Sugar beet damping off	*Rhizoctonia solani*	Sadeghi et al. (2009)
Sugar beet	Sugar beet rhizosphere soil	*Streptomyces* isolates J-2 and B-11	Root rot on sugar beet	*Sclerotium rolfsii*	Errakhi et al. (2009)

by *Phytophthora drechsleri, Rhizoctonia solani* AG-2, and *Fusarium solani*. When sugar beet seeds were treated with *Streptomyces* C isolate it controlled *Rhizoctonia solani* damping off in naturally and artificially infested soils (Sadeghi et al. 2009). So far only genus *Streptomyces* has been used for one amaranthaceae vegetable.

Umbelliferous vegetables

Carrot is only vegetable of the Umbellifery family which has been researched for actinomycetes application (Table 5). Seven actinomycetes strains *Streptomyces janthimts, S. cinerochromogenes, Streptoverticilium netropsis, Actinomadura rubra, Actinoplanes philippinensis, Muromonospora carbonaceae*, and *Streptosporangium albidum* isolated from carrot rhizosphere and screened by in vitro and in vivo antagonism against *Pythium coloratum* Vaartaja, producing non-volatile antifungal metabolites significantly controlled cavity-spot disease of carrot under natural field condition. *Actinoplanes philippinensis* and *Muromonospora carbonaceae* also showed hyperparasitism, and collapsed the pathogen oospore by heavily colonizing it and epiphytically growing on hyphae. This was the first report on microbial control of cavity-spot disease of carrot (El-Tarabily et al. 1997). Root colonizing ability of antagonistic *Streptomyces griseoviridis* was tested on carrot and turnip rape by stand-tube method. It well competed with indigenous soil microbes for root colonization when sufficiently available in soil before seed emergence, but could not compete when applied at later stage, depicting the importance of time of soil spray for root colonization (Kortemaa et al. 1997). Therefore besides searching for competent strains, methodology of bio-formulation development, and its timing of application should also be an integral component of such research projects.

Asteraceae vegetables

Lettuce (*Lactuca sativa*), a leafy vegetable is only member of the family Asteraceae which has been researched for actinomycetes application (Table 5). *Streptomyces viridodiasticus, Micromonospora carbonacea*, and *Serratia marcescens* isolated from lettuce growing field of Al-Ain, United Arab Emiratus significantly reduced growth of *Sclerotinia minor*, a pathogen causing basal drop disease of lettuce in in vitro test, and produced high level of beta-1,3-glucanase and chitinase enzyme (El-Tarabily 2000). Pathogen hyphal plasmolysis and cell wall lysis were noticed when it was given as sole carbon source to the isolated three strains, which were recommended either individually or in combination to control *Sclerotinia minor* led basal drop disease of lettuce under field condition.

Lettuce root and rhizosphere colonization dynamics by genetically modified five *Streptomyces* spp. (transformed by plasmid pIJ8641 for enhanced GFP marker and apramycin resistance) showing strong in vitro inhibition for *Sclerotinia sclerotiorum*, a major soil-borne pathogen of horticultural crops was reported. Tagged ZEA171 strain was found to be both rhizospheric and endophytic as was evident by re-isolation experiment (Bonaldi et al. 2015). This indicate that some of the rhizospheric microbes enter in to plant to become endophytes at later stage. Thus potent endophytic actinomycetes strain(s) may also be applied as rhizospheric application. *Strptomyces exfoliatus* FT05W and *Streptomyces cyaneus* ZEA171 strains available in culture collection of University of Milan, Italy inhibited the growth of soil borne pathogen *Sclerotinia sclerotiorum* causing lettuce drop disease by more than 75% under in vitro test. Furthermore under field condition *S. exfoliatus* FT05W and *S. cyaneus* ZEA171 (10^6 CFU/mL) protected lettuce from drop by 40% and 10% respectively when inoculated a week prior to lettuce showing, while *Streptomyces lydicus* WYEC 108 isolated from commercial product ‘Actinovate’ could not protect the plant (Chen et al. 2016). When applied timely some of these strains may perform better compared with available commercial products. These strains were viable and persistent in the rhizosphere and endorhiza up to 3 weeks as was evident by GFP tagging and SEM analysis. Strain *S. exfoliatus* FT05W has been recommended for controlling this soil borne disease which could not be done by available plant protection products. Only two actinomycetes genera have been applied for one Asteraceae vegetable.

Fabaceae vegetables

Pea (*Pisum sativum*) is only vegetable crop of the Fabaceae family which has been investigated for actinomycetes application (Table 5). Yuan and Crawford (1995) reported that *Streptomyces lydicus* WYEC108 antagonized various plant pathogens in plate assays, and inhibited growth of *Pythium ultimum* and *Rhizoctonia solani* in liquid medium. Pea seeds coated with WYEC108 was 70% protected by *P. ultimum* invasion when planted 24 h prior to pathogen infection. WYEC108 when applied as spore-peat moss-sand formulation (10^8 CFU/g) also showed plant growth promoting traits. Tokala et al. (2002) further investigated the interaction between WYEC108 and pea, and reported increase in root nodulation frequency by acting on *Rhizobium* spp. infection level. Average nodule size was increased as *S. lydicus* colonized and sporulated in it, leading to improved bacteroids vigor by enhanced nodular assimilation of iron and nutrients, and reduced poly-beta-hydroxybutyrate accumulation. It was hypothesized that *Streptomyces* act as plant growth promoting bacteria in pea and other leguminous plants by root and nodules colonization, which has been proved now, and such actinomycetes strains have also been termed as “Rhizobia helper bacteria” [RHB]. Several species

Table 5 Application of actinomycetes in vegetables belonging to Umbelliferae, Asteraceae, Fabaceae, Amaryllidaceae, Asparagaceae, Amaranthaceae, Zinzgiberaceae families

Crops/vegetables	Source of isolation	Actinomycetes	Trait(s)	Pathogen(s)	References
Carrot	Carrot rhizosphere	*Streptomyces janthinus, S. cinerochromogenes, Streptoverticillium netropsis, Actinomadura ruhra, Actinoplanes philippinensis, Micromonospora carbonaceae*, and *Streptosporangium albidum*	Biocontrol	*Pythium coloratum* Vaartaja, a causal agent of cavity-spot disease of carrots (*Daucus carota*)	El-Tarabily et al. (1997)
Turnip rape and carrot	Culture collection	*Streptomyces griseoviridis*	Root colonization ability	–	Kortemaa et al. (1997)
Lettuce	Culture collection, University of Milan	genetically modified [GFP] *Streptomyces* spp.	PGP and Biocontrol	*Sclerotinia sclerotiorum*	Bonaldi et al. (2015)
Lettuce	Culture Collection, University of Milan	*S. exfoliatus* FT05W, *S. cyaneus* ZEA17I	Biocontrol of soil borne disease, Lettuce drop	*Sclerotinia sclerotiorum*	Chen et al. (2016)
Lettuce	Lettuce rhizospheric soil	*Micromonospora carbonacea*	Basal drop disease of lettuce	*Sclerotinia minor*	El-Tarabily et al. (2000)
Pea plant (*Pisum sativum*)	Rhizosphere soil of linseed	*Streptomyces lydicus* WYEC108	Enhanced root nodulation, at the level of infection by *Rhizobium* spp.	–	Tokala et al. (2002)
Sweet pea	Endophytic actinomycetes of sweet pea	*Streptomycetes* sp. P4-isolate	Biocontrol	*Oidium* sp. powdery mildew pathogenic fungus	Sangmanee et al. (2009)
Pea seeds	Soil samples	*Streptomyces lydicus* WYEC108	Pythium seed rot and root rot	*Pythium ultimum* or *Rhizoctonia solani*	Yuan and Crawford (1995)
Pea	Rhizospheric soils	*Streptomyces* St7c5	Foot rotting and blight	*Mycosphaerella pinodes*	Mohamed and Benali (2010)
Transgenic pea	Culture collection	chitinase (Chit30) from *Streptomyces olivaceoviridis* ATCC 11238	Inhibition or delay of hyphal extension of *T. harzanium*	*Trichoderma harzanium*	Hassan et al. (2009)
Onion	Egyptian soils	*Streptomyces coelicolor* HHFA2	Onion bacterial rot disease	*Erwinia carotovora* subsp. *carotovora* and *Burkholderia cepacia*	Abdallah et al. (2013)
Asparagus	Asparagus field soil	*Streptomyces* spp. (ME2-27-19A)	Asparagus decline syndrome	*Fusarium oxysporum* f.sp. *asparagi* (FOA), *F. moniliforme* (FM)	Elson et al. (1994)
Table beet, bush beans	Clay granules	*Actinoplanes* spp.	Reducing *Pythium* damping-off of plants	*Pythium ultimum*	Khan et al. (1997)
Ginger	Soil	*Streptomyces* species (SSC-MB-01 to SSC-MB-06)	Biocontrol	*Fusarium oxysporum* f.sp. *zingiberi*	Manasa et al. (2013)

of genus *Micromonospora* have recently been reported to play a significant role in nodular tissues of both leguminous and actinorhizal plants (Trujillo et al. 2015; Martínez-Hidalgo et al. 2014). Actinomycetes rhizobia consortia will soon be replacing currently used rhizobia based nodulating agents. Endophytic *Streptomyces* spp. isolated from sweet pea when inoculated by seed and three foliar spray at 15, 34, and 49 days after transplantation significantly reduced the leaf damage by powdery mildew when infected by pathogenic fungus *Oidium* sp. 67 DAT (Sangmanee et al. 2009). Therefore in addition to timing of application, plant parts to be treated should also be worked out. When Chit30 (a family 19 chitinase) from *Streptomyces olivaceoviridis* ATCC 11238 was expressed in transgenic pea it inhibited and delayed *Trichoderma harzanium* hyphal extension because of enhanced antifungal activity when compared with non-transgenic control plant (Hassan et al. 2009). These actinomycetes strains may also work as a source of useful genes for generating transgenic crops. Pea seeds treated with talc formulation of *Streptomyces* St7c5, a rhizospheric isolate enhanced seed germination, showed plant growth promotion, and significantly reduced root rotting and blight caused by *Mycosphaerella pinodes* (Mohamed and Benali 2010). Actinoplane strain 25,844 (10^8 CFU/g of granules) at 1% (w/w) increased bush beam emergence on being planted in *Pythium ultimum* infested plots after 28 days (Khan et al. 1997). Three genera of actinomycetes (*Streptomyces, Micromonospora, Actinoplanes*) have been used for single Fabaceae vegetable.

Amaryllidaceae family vegetable

There is only one report on management of onion bacterial rot disease using actinomycetes as biocontrol agent (Table 5). Egyptian soil isolates *Streptomyces lavendulae* HHFA1 and *Streptomyces coelicolor* HHFA2 controlled onion bacterial rot in pot and field experiments, and also showed plant growth promoting effect by enhanced photosynthetic pigments and foliar growth. *S. coelicolor* HHFA2 significantly reduced onion bacterial rot disease incidence throughout the post harvest storage period compared with untreated control, and has been recommended as biological control agent for onion bacterial rot disease (Abdallah et al. 2013).

Asparagaceae family

There is only one report by Elson et al. (1994) on *Streptomyces* spp. (ME2-27-19A) isolated from asparagus field soil inhibiting *Fusarium oxysporum* f.sp. *asparagi* (FOA) and *F. moniliforme* (FM) causing asparagus decline syndrome of asparagus root and crown respectively (Table 5). Chromatographically purified compound(s) obtained by solvent extraction of *Streptomyces* strain ME2-27-19A inhibited FAO and FM at 40 mg/ml, and at 100 mg/ml when applied in soil but asparagus shoot length was also reduced. Therefore it is desirable that researchers should optimize the strains for both biocontrol and PGP traits.

Amaranthaceae family

Khan et al. (1997) has reported augmentation of field soil with *Actinoplanes* spp. sporangia for biological control of *Pythium* damping-off (Table 5). *Actinoplanes* strain 25,844 increased growth and reduced root rot of table beet compared with control when applied at 5% (w/w) as granules ($4 \times 10^7 – 4 \times 10^8$ CFU/g of granules) to *P. ultimum* (750–1000 oospores/g) infested soil. Hyper-parasitic activity of strain 25,844 for *P. ultimum* oospores was reported even on six month old granules.

Zinzgiberaceae family

Manasa et al. (2013) screened *Streptomyces* sp. (SSC-MB-01 to SSC-MB-06) for biocontrol potential against *Fusarium oxysporum* f.sp. *zingiberi* causing rhizome rot of ginger by dual plate method, and also by using ethyl acetate extract of broth by agar diffusion test. *Streptomyces* sp. SSC-MB-02 showed best inhibitory activity while strain SSC-MB-05 did not inhibit pathogen in both the test. *Streptomyces* strain SSC-MB-02 has been recommended for controlling soft rot symptoms of ginger rhizome (Table 5).

Commercial strains available

There are nine actinomycetes based products available in the market worldwide and ten active substances registered as commercial products, and all of them have been prepared using different species of the genus *Streptomyces* (Kabaluk et al. 2010; Aggarwal et al. 2016; Vurukonda et al. 2018), besides few other strains are at various stages of development in different laboratories in order to get commercial status. Mycostop and Actinovate are two of these actinomycetes based commercial products which have been in use globally for a long time. Mycostop, registered as microbial pesticide in Canada, European Union and USA, inhibits soil and seed borne fungal pathogens, and has been prepared using *Streptomyces griseovirids* isolated from Finnish Sphagnum peat (White et al. 1990). Seed and soil treated with 'Mycostop' inhibits seed and soil borne fungal pathogens because of antifungal aromatic heptaene polyene antibiotic secretion by *S. griseovirids* K61 strain. Like *Alternaria brassicicola* on cauliflower and cabbage, and *Botrytis cinerea* on lettuce were controlled by 'Mycostop' application, besides it is also being used to control *Fusarium, Phytophthora*, and *Pythium* led wilt and root diseases in different crops. While

Actinovate, registered in Canada and USA, inhibits the growth of *Pythium ultimum* and *Rhizoctonia solani* besides showing plant growth promoting traits, and has been prepared using *Streptomyces lydicus* WYEC 108 strain (Yuan and Crawford 1995). Soil borne diseases like those being caused by *Pythium, Fusarium, Phytophthora, Rhizoctonia, Verticillium*, foliar diseases such as powdery and downy mildew, and those being caused by *Botrytis* and *Alternaria, Postia, Geotrichum*, and *Sclerotinia* can be controlled using Actinovate (Vurukonda et al. 2018). Mykocide KIBC controlling powdery mildews, grey mold, brown patch and Safegrow KIBC being used for sheath blight and large patch are registered in South Korea. Actofit targeting Colorado potato beetle, web mites and other phytophags, while Bactophil controlling seed germination diseases are registered in Ukraine. Incide SP and Actin being used as insecticides and fungicide respectively are registered in India, while well known Bialaphos being used as herbicide is registered in USA (Kabaluk et al. 2010).

Among the list of active substances derived from actinomycetes, Abamectin (Avermectins) registered globally targets beetles, mites, leaf miners, suckers and other insects of vegetables and other crops. Streptomycin, Phytomycin, Validamycin, and Polyoxorim registered in Canada, China, India, New Zealand, Ukrain, and USA control various bacterial and fungal led diseases of vegetables and other crops. Polynactin controlling different types of mites, and Milbemycine controlling mites and leaf miners in eggplant are registered in Japan. While Blasticidin-S controlling rice blast and Kasugamycin controlling *Phytophthora* led root rot and leaf spot in different crops are registered in USA and Ukraine respectively (Aggarwal et al. 2016).

Conclusions and future perspectives

In general potential actinomycetes strain has been isolated either from rhizospheric soil sample, and/or as endophyte of same or different crop. Usually researchers have focused on roots of healthy plants while searching for potent endophytes, but the diseased plants and also other parts of plant like stem and leaves should not be ignored. Focus should also be on isolation of rare actinomycetes and still unexplored actinomycetes genera using different newly reported media. Actinomycetes strain inhibiting specific pathogen affecting different vegetable crops, and also strain inhibiting different pathogens because of its broad spectrum of activity should be the target of research. Such potent strain should be further optimized for its PGP and other useful traits. Consortium approach should be open not only to different species and genera of actinomycetes, but also to different groups of microorganisms and its culture filtrates, besides looking for combined application with different chemicals and/or organic substitutes. Bioformulation development, and its application on particular part of plant at specific time should be well established. Strain specificity of both partners should be workout before using actinomycetes rhizobia consortia. Biotechnological expertise need to be develop to convert any actinomycetes strain into competent potential strain either by activating silent genes, and/or by transfer of genes from other strains using modern genetic engineering and synthetic biology tools.

It is quite evident that a limited group of vegetables belonging just to 11 families have only been researched for actinomycetes application. Many vegetable families are not even touched, and single publication on application of actinomycetes to only one vegetable crop belonging to family like Amaryllidaceae, Asparagaceae, Amaranthaceae, and Zinzgiberaceae itself speak the scope for future research. Furthermore even among the 12 orders with 162 genera of actinomycetes only few have got researchers attention. Future research programme should not only target still untouched vegetables, but should also focus on still unexplored genera of this very promising group of microorganisms isolated from different sources including endophytes. Exploration of multifunctional actinomycetes strains having optimized traits combination of biocontrol, PGP, herbicidal, and pesticidal activities should be the target of future research.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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