IJCSPUB.ORG ISSN : 2250-1770
INTERNATIONAL JOURNAL OF CURRENT SCIENCE (IJCSPUB)
IJCS PUBLICATION (IJCSPUB.ORG) An International Open Access, Peer-reviewed, Refereed Journal

POTASSIUM SOLUBILIZING ACTINOMYCETES: A SUSTAINABLE APPROACH FOR POTASSIUM MINERAL DEFICIENCY IN SOIL

SREEJA BOPIN [1]*, KALAVATI PRAJAPATI [2]

[1]*Research Scholar , [2]Assistant Professor,
[1]* Department of Microbiology , HVHP Institute of Post Graduate Studies and Research,
KSV, Kadi, (North Gujarat), India.

Abstract : Plants need nutritional elements for their better growth and development. Some of these elements are considered essentials, such as nitrogen (N), phosphorus (P), and potassium (K).These nutrients can be found in the soil as a result of the breakdown of vegetable or animal organic matter, or by the application of mineral fertilizers. Insufficient replacement of these nutrients in the soil can result in nutritional depletion, poor growth and crop yield decline. Therefore, the nutritional status of plants depends mainly on the availability of nutrients in the soil where they are cultivated. Soils with adequate mineral composition will provide the necessary elements for greater productivity and, as a result, foods of higher nutritional quality. The potassium solubilizing actinomycetes, KSAs are most important microorganisms for solubilizing fixed form of K in soil system. According to the literature, currently negligible use of potassium fertilizer as chemical form has been recorded in agriculture for enhancing crop yield. Most of the farmers use only nitrogen and phosphorus and not the K fertilizer due to unawareness that the problem of K deficiency occurs in rhizosphere soils.

Key words: Potassium solubilization, actinomycetes, mineral deficiency, soil fertility, agriculture.

1. INTRODUCTION:

As per the increasing population, demand for food is increasing (Fukase and Martin, 2020). By 2050, the world's population is predicted to exceed 8 billion people, becoming huge challenge for agricultural systems to produce enough food to feed for this growing global population (Prosekov and Ivanova 2018) In agricultural and productivity also support this demand by the soil's poverty in macronutrients, especially nitrogen, potassium and phosphorus (Mekuria, 2018). To overcome this problem, the use of agrochemicals was the primary option to satisfy the crops needs in order to obtain higher yields. Although uncontrolled and improper usage of agrochemicals adversely affect soil ecosystem, agricultural sustainability and human health (Mma and Mfm, 2014). So it is an innovative, cost-effective, and eco-friendly strategy has to implement to achieve the same goal as agrochemicals fertilizers. Here the importance of actinomycetes because as a microbe can increase soil fertility through mineral solubilization, nitrogen fixation, organic matter decomposition, mineralization, and storage (Jangra et al., 2018; Soumare et al., 2020b; Svenningsen et al., 2018). Among beneficial microbes, Actinomycetes genus is one of the most abundant bacterial group and plays a major role in biotechnological applications. Indeed, Actinomycetes species are economically and biotechnologically most worthwhile microorganisms which play an unequivocal role on plant growth and yield (Bhatti et al., 2017; Boubekri et al., 2021; Soumare et al., 2020a). In fact, many actinomycetesl strains are reported as potassium and/or phosphate solubilizing bacteria (KSB and PSB respectively), symbiotic or free-living diazotrophs (Dahal et al., 2017), plant growth promoting and biocontrol agents (anti-virus, antifungal etc.), biotic stress and plant probiotics (Alekhya and Gopalakrishnan, 2017). Among Actinomycetes, K and P solubilizing Actinomycetes have attracted the attention of agriculturists to use them as soil inoculums to increase the plant growth and yield. Different Actinomycetes strains, especially those belong in Streptomyces genus are reported to be involved in crops growth in development (Hamedi and Mohammadipanah, 2014; Nandimath et al., 2017). The present review discusses the beneficial role of Actinomycetes for sustainable agricultural production. In addition, it covers the main mechanism of K solubilization by actinomycetes and their main PGP traits in crops development. In conclusion discussed with a few viewpoints of Actinomycetes for future agriculture.

2. ACTINOMYCETES AN OVERVIEW:

Actinomycetes are Gram-positive earthly bacteria. Previously, they were classified in a unique group since they lie between true fungi and bacteria. Compared to other Gram-positive bacteria, they exhibit great morphological differentiation. They produce a profuse mycelium and chains of aerial conidia similar to those of fungi imperfect (Subramaniam et al., 2016). However, their cellular structures are identical to prokaryotes and are totally different with fungi. In addition, their cell walls do not contain chitin or cellulose as all bacteria, whereas those of fungal hold a high among of chitin. They are unicellular like all bacteria and their mycelium is nonseptate, more slender unlike that of fungi (Qinyuan et al., 2016). Based on these criteria, they are closer taxonomically to Bacteria than to Fungi and are recognized as belonging to Bacteria. Actinomycetes are saprophytes, ubiquitous and are one of the most diverse groups of bacteria in nature. Their nature varies from anaerobic unicellular organisms to aerobic, filamentous and spore forming lineages (Lewin et al., 2016). Actinomycetes found eventually in all ecosystems especially those with a higher pH (Lauber et al., 2009) such as soil, water, humus, litter, deep sea, rock phosphate and as entophytes in plants (Araújo et al., 2000; Hamdali et al., 2008a; Kamjam et al., 2017; Liu et al., 2019; Nafis et al., 2019; Sharma et al., 2014). Most of them represent 30% of the total soil micro biomes just after the rainfall (Bouizgarne and Aouamar, 2014; Polti et al., 2014). In fact, they responsible for the wet earth odour due to the production of an earthy-smelling substance named "geosmin" (Amoroso et al., 2013). It is their ability to grow in the extreme environments by the synthesis of secondary metabolites (Lee et al., 2018) and extracellular hydrolytic enzymes, which are responsible to breakdown animal and plant biomass and thus making them central organisms in carbon recycling. For example, degradation / decomposition of different organic substances such as cellulose, polysaccharides, protein fats, organic acids and humus via cellulase and chitinase production (Bhatti et al., 2017; El-Tarabily et al., 1996; Jiang, 2016) and it helps indirectly to promote the plant growth.

Among Actinomycetes, Cellulomonas, Nocardia and Micromonospora have been already reported to be implicated in plant biomass degradation in soil. However, the most predominant recorded group was Streptomyces species especially in dried non-acidic soil with high organic matter content (Bontemps et al., 2013; Chen et al., 2018; Hirsch and Vald´es, 2010; Lewin et al., 2016). Under a stressful condition, some Actinomycetes forced to sporulation for its survival.(Ouhdouch et al., 2001). The classification and taxonomy were based on phenotypic criteria like morphology such as colour of colony, spores chain morphology, the surface structure of the spore etc. They have a diverse form ranging from coccoid (Micrococcus) and rods (Mycobacterium) to branching mycelium (Streptomyces). Based on their frequency terrestrial soil, Actinomycetes were divided into two groups namely Streptomyces and non-Streptomyces or rare Actinomycetes (Wink et al., 2017). Indeed, Streptomyces represent up to 95% of total actinomycetes isolated, followed by Nocardia (2%), then Micromonospora (1%) and the rest includes Thermomonospora, Actinoplanes, Microbispora, and others (Arifuzzaman et al., 2010; Balagurunathan et al., 2010). From a genetic point of view, Actinomycetes are the largest bacterial phyla with a genome size ranging from 0.93 to 11.9 megabases (Mb) and have a high content of guanosine-cytosine (Barka et al., 2016; Miao and Davies, 2010). It ranges from 42% in some Gardnerella vaginalis to 74.4% in Kineococcus radiotolerans (Verma et al., 2013). The taxonomy of Actinomycetes is extremely complex (Soumare et al., 2020b).

According to Bergey's manual (volume 5), the phylum of Actinomycetes was then divided into 6 classes namely Actinomycetes, Acidimicrobiia, Coriobacteriia, Nitriliruptoria, Rubrobacteria and Thermoleophilia. Nowadays, 16 RNA analyses are the most significant for Actinomycetes identification and are commonly employed. However, the new or existing species based on 16 rRNA gene sometimes becomes problematic and create uncertainty due to the low consonance level (Verma et al., 2013). In current research, supports in order to discriminate between closely related genera including rpoB and ssgB (Girard et al., 2013). In the other hand, Verma et al. (2013) demonstrated phylogenetic studies of Actinomycetes. According to new classification, Salam et al. (2020) have rearranged the 425 genera of the phylum 'Actinomycetes' into 6 classes, 46 orders and 79 families, including 16 new orders and 10 new families.

3. ACTINOMYCETES AND ITS POTASSIUM SOLUBILIZATION ABILITY TO PROMOTE PLANT GROWTH:

In the agriculture field so far used 80–90% of mined P/K in total world demand (Tirado and Allsopp, 2012). Based on this, the challenges of developing sustainable agriculture, the direct use of rock phosphate as K-fertilizer and its solubilization through microorganisms have become a centre of attraction. According to the Web of Science database, from2000 to 2020, ~949 indexed research articles have been published under the following keywords "Actinomycetes and phosphate solubilization" and "Actinomycetes and plant growth". Among them, ~879 are related to "Actinomycetes and plant growth" i.e. 92.62% of all publications in this field (Boubekri et al.,2022).According to the collected data, this is a clear indication showing the importance of this topic for researchers around the world. Detailed analysis of these publications showed that PSA have been isolated in different environment such as ceramic soil (Sreeja and Prajapati K., 2021) mining soils (Biglari et al., 2016; Hamdali et al., 2011; Nafis et al., 2019; Syiemiong and Jha, 2019), forest soil (Balakrishna et al., 2012), rhizospheric soil (Anwar et al., 2016; Vasconcellos et al., 2010) and marine environments (Dastager and Damare, 2013). Among these Actinomycetes, species belonging to the genus Streptomyces have been found to be the most predominant one in term of phosphate solubilization (Jog et al., 2014; Purushotham et al., 2018). In this regard, Gong et al. (2018) have demonstrated that 17.4% of the rhizospheric isolates exhibited phosphate solubilization capacities and were classified as Streptomyces spp. Similar results were reported by Nafis et al. (2019) who showed a highest P solubilization activity by two Streptomyces (Streptomyces sp. TNC-1 and Streptomyces sp. MNC-1), isolated from mountain and deserts soils. Their solubilization capacity were 12.39 and 8.56 mg/ml respectively. Others workers such as (Anwar et al., 2016; Chaiharn et al., 2018; Fatmawati et al., 2019; Hamdali et al., 2012; Jog et al., 2012) have shown the important role of Streptomyces as phosphate solubilizers. Generally, among the *Streptomyces* spp., *S. thermolilacinus*,*S. youssoufiensis*, *S. rochei*, and *S. carpinensis*have been reported as the best P-solubilizing isolates (Hamdali et al., 2011, 2008a; Jog et al., 2014, 2012; Sreevidya et al., 2016). Surprisingly Actinomycetes displayed also the potential to solubilize phosphorus also such as Dastager and Damare (2013) reported that Microbacterium, Angustibacter, Kocuria, Isoptericola and Agromyces, isolated from Mangroves sediments, were also phosphate solubilizers.Comparitively similar results were recorded with Microbacterium sp MBS3R isolated by Lunggani and Suprihadi (2019). Thesolubilization capacity of Actinomycetes is often correlated with a positive impact on the growth of plants. Nowadays, some K-solubilizing Actinomycetes are used for commercial biofertilizers. In the market, Actinovate, Mycostop, Actofit and Astur are already available. These products are formulated from different strains. For instance, Actinovate, is based on *S. lydicus* WYEC 108, Mycostop is based on Streptomyces K61 and Actofit and Astur is based on *S. avermitilis*., several strains cited in the scientific literature as potentially useful were do not appear at the commercial level, probably because of their inappropriate formulation (Bashan et al., 2013). This shows disparity among the research and development of potential actinomycetes formulations for field application. Actinomycetes produce organic acids involved in solubilization. The type of acid produced depends on the species of Actinomycetes. For example, it was found that lactic and 2-ketogluconic acids were the predominant acids found in Streptomyces (Banik and Dey, 1982),while malic acid was detected as the main organic acid produced by *S. thermolilacinus* IDWR81 (Jog et al., 2012). Some Actinomycetes such as *Micromonospora endolithica* have a broad spectrum of organic acid production and also reported to be capable of producing lactic, oxalic, gluconic, succinic, acetic, malic and citric acids (El-Tarabily et al., 2008). In addition to acid production, chelation would be an efficient solubilization mechanism for some Actinomycetes (Delvasto et al., 2006; Nandimath et al., 2017; Sharma et al., 2014; Hamdali et al., 2011). Based on this some Actinomycetes are reported to be able to produce hydroxamate as main siderophore which chelates iron from phosphate and release phosphate ions in soil solution (Shanmugaiah et al., 2015). Actinomycetes harbor other undiscovered pool of siderophores, which remain to be explored (Nett et al., 2009; Rebets et al., 2014).

4. CROPS IMPROVEMENT THROUGH PLANT GROWTH REGULATORS PRODUCTION:

An interesting fact of Actinomycetes is their capacity to produce plant growth hormones such as auxins, gibberellins, cytokinins, ethylene and abscisic acid (Franco-Correa et al., 2010; Franco-Correa and Chavarro-Anzola, 2016; Nath Yadav, 2017; Yadav and Nath Yadav, 2019). Among plant growth promoting Actinomycetes, Streptomyces group are commonly known as the most promising actinomycetes group as IAA producers (Khamna et al., 2010) and plant growth promoters (Wahyudi et al., 2019). Various Streptomyces including *S. violaceus*, *S. griseus*, *S. exfoliates*, *S. coelicolor*, and *S. lividans* were reported to be able to produce IAA and their pathways of its synthesis was investigated by Manulis et al. (1994).Most relevant relationship between IAA production and plant growth by Streptomyces has been also discussed by Htwe et al. (2019) who revealed that inoculation of *S. griseoflavus* P4 produced IAA between 0.8 and 2.8 mg.L-1 and enhanced the growth of soybean, sweet pea, rice, spinach, maize, and wheat. More than that Dochhil et al. (2013) isolated two endophytic Streptomyces from *Centella asiatica* and described their higher concentrations of IAA production (71 g/ml and 197 g/ml) which enhance effectively the percentage of seed germination. On the other hand, Actinomadura, Nocardia, Nonomuraea, were also reported to produce IAA (Khamna et al., 2009). These results have shown that IAA is the most studied plant growth promoting regulators production traits by actinomycetes and have a considerable role in the stimulation of plant cell division and root elongation, etc. However, some metabolites like pteridic acids A and B produced by endophytic Streptomyces hygroscopicus TP_A045 showed also an auxin-like activity and induce the formation of adventitious roots in hypocotyls of kidneys beans (Igarashi et al., 2002). Through these phyto hormones, Actinomycetes improve the growth and yield of several crops (Soumare et al., 2020a). At least ten research papers for each plant species have been evaluated to appreciate their yield increments. The results absolutely proved that all tested Actinomycetes increase the yield. The effect was higher in wheat followed by maize, tomato, and rice. The lowest yield increment was recorded in chickpea plant. These differences highlight the importance of the plant species-Actinomycetes interactions. In fact, based on the literature, it has been found that Streptomyces are the most common species covering and improving a broad array of crop plants . The microorganism for the plant is one of the finest gifts of nature and may provide key insights of biological phenomenon to boost the plant growth and nourishment (Ma et al., 2016). However differences of the yield increment could be also explained by the type of the root exudates produced by the plant's species. In fact, depending upon the characteristics of root exudates, the plant-Actinomycetes interactions can be affected either positively or negatively (Vishwakarma et al., 2017).

5. SUSTAINABLE APPROACH FOR POTASSIUM MINERAL DEFICIENCY IN SOIL:

The concentration of soluble form of K in soil is very less in amount than in insoluble form. Silt, clay and sand are important components of soil in earth and are biggest reservoir of potassium. In common form of potassium are in feldspar and mica. The available K level in soil dropped in the last decade due to rapid development of agriculture and application of imbalanced fertilizers. Potassium is released only when these minerals are slowly weathered or solubilized by some beneficial microorganisms and made available for plants. Several bacterial, fungal and actinomycetes strains have been identified for their ability of high potassium solubilization. Soluble potassium is the most available form but its contribution to total K is very small. Being essential or vital nutrient for plant growth, potassium (K+) plays an important role in plant regulatory development including osmoregulation, plant-water relation and internal cation/anion balance. It also has substantial effect on enzyme activation involved in the formation of organic substances, protein and starch synthesis, respiratory and photosynthetic metabolism (Marschner 2010)Potassium helps in stimulating the growth of young tissues and cell enlargement and, hence, improves early growth. Besides, potassium is important during plant ontogeny and in improving plant quality and oil content in plants. Hence, large amount of potassium is required to maintain plant health but it often receives less attention than N and P in many crop production systems. The crop yield can be positively and negatively influenced by favourable and unfavourable environmental conditions. Unfavourable environmental conditions which would create potentially damaging physiological changes within plants are known as stresses (Shao et al. 2008). Potassium has also been involved in various physiological functions related to plant health and resistance to biotic and abiotic stresses such as diseases, pests, drought, salinity, cold, frost and waterlogging (Wang et al. 2013)Basically, K+ is water soluble and highly mobile and transported to the xylem in plants (Lack and Evans 2005). It plays an important role in regulation mechanism in plants since it is constituent of 60 different enzyme systems of drought tolerance and water-use efficiency. K deficiency, also known as potash deficiency in soil /plants, occurs strong impact on plant metabolism. A plenty of deficiency symptoms have been reported which include chlorosis, poor growth, reduced yield and poor fibre quality with the increased susceptibility to diseases (Amtmann et al. 2008) and pests (Amtmann et al. 2006; Troufflard et al. 2010). It also affects photosynthesis process and plant growth; hence, purple spots may also appear on the leaf undersides. Besides, older leaves change from yellow to brown, leaf tips and margins dry up, root oxidation power declines, younger leaves decolourize, and root length and density reduce causing reduction of nutrient uptake and cytokine production in roots.

ACKNOWLEDGEMENT

The authors are thankful to the Department of Microbiology, HVHPGR, Kadi and Management of Kadi Sarva Vishwavidyalaya (KSV), Gandhinagar, for providing the facilities for this research.

REFERENCES

[1] Alekhya, G., Gopalakrishnan, S., 2017. Biological control and plant growth-promotion traits of streptomyces species under greenhouse and field conditions in chickpea. Agric. Res. 6, 410–420. https://doi.org/10.1007/s40003-017-0278

[2] Amoroso, M.J., Benimeli, C.S., Cuozzo, S.A., 2013. Actinomycetes: application in bioremediation and production of industrial enzymes. Actinobact. Appl.Bioremediat. Prod. Ind. Enzym. https://doi.org/10.1201/b14776.

[3] Araújo, J.M., de, Silva, A.C., da, Azevedo, J.L., 2000. Isolation of endophytic actinomycetes from roots and leaves of maize (Zea mays L.). Braz. Arch. Biol. Technol. 43, 447–451. https://doi.org/10.1590/s1516-89132000000400016.

[4] Arifuzzaman, M., Khatun, M.R., Rahman, H., 2010. Isolation and screening of actinomycetes from Sundarbans soil for antibacterial activity. Afr. J. Biotechnol. 9, 4615–4619. https://doi.org/10.5897/AJB10.339.

[5] Balagurunathan, R., Radhakrishnan, M., Somasundaram, S.T., 2010. L-glutaminaseproducing actinomycetes from marine sediments-selective isolation, semiquantitative assay and characterization of potential strain. Aust. J. Basic Appl. Sci. 4, 698–705.

[6] Barka, E.A., Vatsa, P., Sanchez, L., Nathalie Gaveau-Vaillant, C.J., Klenk, H.-P., Cl´ement, C., Ouhdouch P., Y., van Wezeld, G., 2016. Taxonomy, physiology, and natural products of Actinomycetes. Micro Mol. Biol. Rev. 80, 1–43. https://doi.org/10.1128/MMBR.00019-15.

[7] Bhatti, A.A., Haq, S., Bhat, R.A., 2017. Actinomycetes benefaction role in soil and plant health. Microb. Pathog. 111, 458–467. https://doi.org/10.1016/j.micpath.2017.09.036.

[8] Biglari, N., Hassan, H.M., Amini, J., 2016. The Ability of Streptomyces spp. Isolated from Iranian soil to solubilize rock phosphate. Adv. Biosci. Clin. Med. 4, 15–25. https://doi.org/10.7575/aiac.abcmed.16.04.03.03.

[9] Bontemps, C., Toussaint, M., Revol, P.V., Hotel, L., Jeanbille, M., Uroz, S., Turpault, M.P., Blaudez, D., Leblond, P., 2013. Taxonomic and functional diversity of Streptomyces in a forest soil. FEMS Microbiol. Lett. 342, 157–167. https://doi.org/10.1111/1574-6968.12126.

[10] Boubekri, K., Soumare, A., Mardad, I., Lyamlouli, K., Hafidi, M., Ouhdouch, Y., Kouisni, L., 2021. The screening of potassium- and phosphate-solubilizing actinomycetes and the assessment of their ability to promote wheat growth parameters. Microorganisms 9, 1–16. https://doi.org/10.3390/microorganisms9030470.

[11] Boubekri, K., Soumare, A., Mardad, I., Lyamlouli, K., Ouhdouch, Y., Hafidi, M., & Kouisni, L.,2022. Multifunctional role of Actinobacteria in agricultural production sustainability: a review. Microbiological Research, 127059.

[12] Bouizgarne, B., Aouamar, A.A.B., 2014. Diversity of plant associated actinomycetes.Bact. Divers. Sustain. Agric. https://doi.org/10.1007/978-3-319-05936-5.

[13] Chen, Y., Zhou, D., Qi, D., Gao, Z., Xie, J., Luo, Y., 2018. Growth promotion and disease suppression ability of a Streptomyces sp. CB-75 from banana rhizosphere soil. Front. Microbiol. 8, 1–18. https://doi.org/10.3389/fmicb.2017.02704.

[14] Dahal, B., NandaKafle, G., Perkins, L., Bro¨zel, V.S., 2017. Diversity of free-Living nitrogen fixing Streptomyces in soils of the badlands of South Dakota. Microbiol. Res. 195, 31–39. https://doi.org/10.1016/j.micres.2016.11.004.

[15] Dastager, S.G., Damare, S., 2013. Marine actinomycetes showing phosphate-solubilizing efficiency in Chorao Island, Goa, India. Curr. Microbiol. 66, 421–427. https://doi.org/10.1007/s00284-012-0288-z.

[16] Dochhil, Hmingthangziki, Dkhar, Mamtaj S., Barman, D.I.N.A., et al., 2013. Seedgermination enhancing activity of endophytic Streptomyces isolated fromindigenous ethno-medicinal plant Centella asiatica. Int J. Pharm. Biol. Sci. 4,256–262.

[17] El-Shatoury, S.A., Ameen, F., Moussa, H., Wahid, O.A., Dewedar, A., AlNadhari, S., 2020. Biocontrol of chocolate spot disease (Botrytis cinerea) in faba bean using endophytic actinomycetes streptomyces: a field study to compare application techniques. PeerJ 2020. https://doi.org/10.7717/peerj.8582.

[18] El-Tarabily, K.A., Sykes, M.L., Kurtbo¨ke, I.D., Hardy, G.E.S.J., Barbosa, A.M., Dekker, R.F., 1996. Synergistic effects of a cellulase producing Micromonospora carbonaceaand an antibiotic producing Streptomyces violascens on the suppression of Phytophtora cinnamoni root rot of Banksia grandis. Can. J. Bot. 74, 618–624.

[19] El-Tarabily, K.A., Nassar, A.H., Sivasithamparam, K., 2008. Promotion of growth of bean (Phaseolus vulgaris L.) in a calcareous soil by a phosphate-solubilizing, rhizosphere-competent isolate of Micromonospora endolithica. Appl. Soil Ecol. 39, 161–171. https://doi.org/10.1016/j.apsoil.2007.12.005.

[20] Franco-Correa, M., Chavarro-Anzola, V., 2016. Actinomycetes as plant growth-promoting rhizobacteria. Actinobact. Basics Biotechnol. Appl. https://doi.org/10.5772/61291.

[21] Franco-Correa, M., Quintana, A., Duque, C., Suarez, C., Rodríguez, M.X., Barea, J.M., 2010. Evaluation of actinomycete strains for key traits related with plant growth promotion and mycorrhiza helping activities. Appl. Soil Ecol. 45, 209–217. https://doi.org/10.1016/j.apsoil.2010.04.007.

[22] Fukase, E., Martin, W., 2020. Economic growth, convergence, and world food demand and supply. World Dev. 132, 104954

https://doi.org/10.1016/j.worlddev.2020.104954.

[23] Jangra, M.R., Jangra, S., Nehra, K.S., 2018. Role of Microbes in Agriculture. Crop Improvement for. Sustainability 193–222. https://doi.org/10.1007/978–3-319–99768-1_9.

[24] Hamdali, H., Virolle, M.J., von Jan, M., Spro¨, C., Klenk, H.P., Ouhdouch, Y., 2011.Streptomyces youssoufiensis sp. nov., isolated from a Moroccan phosphate mine. Int. J. Syst. Evolut. Microbiol. 61, 1104–1108. https://doi.org/10.1099/ijs.0.023036-0.

[25] Hamdali, H., Moursalou, K., Tchangbedji, G., Ouhdouch, Y., Hafidi, M., 2012. Isolation and characterization of rock phosphate solubilizing actinomycetes from a Togolese phosphate mine. Afr. J. Biotechnol. 11 (2), 312–320. https://doi.org/10.5897/AJB11.774.

[26] Hamedi, J., Mohammadipanah, F., 2014. Biotechnological application and taxonomical distribution of plant growth promoting actinomycetes. J. Ind. Microbiol. Biotechnol. 42, 157–171. https://doi.org/10.1007/s10295-014-1537-x.

[27] Hirsch, A.M., Vald´es, M., 2010. Micromonospora: an important microbe for biomedicine and potentially for biocontrol and biofuels. Soil Biol. Biochem. 42, 536–542. https://doi.org/10.1016/j.soilbio.2009.11.023.

[28] Htwe, A.Z., Moh, S.M., Soe, K.M., Moe, K., Yamakawa, T., 2019. Effects of biofertilizer produced from bradyrhizobium and streptomyces griseoflavus on plant growth, nodulation, nitrogen fixation, nutrient uptake, and Seed Yield of Mung Bean, Cowpea, and Soybean. Agronomy 9. https://doi.org/10.3390/agronomy9020077.

[29] Igarashi, Y., Iida, Y., Yoshida, R., Furumai, T., 2002. Pteridic acids A and B, novel plant growth promoters with auxin-like activity from Streptomyces hygroscopicus TP-A0451. J. Antibiot. 55, 764–767. https://doi.org/10.1007/978-1-4614-7990-1.

[30] Jog, R., Nareshkumar, G., Rajkumar, S., 2012. Plant growth promoting potential and soil enzyme production of the most abundant Streptomyces spp. from wheat rhizosphere.J. Appl. Microbiol. 113, 1154–1164. https://doi.org/10.1111/j.1365-2672.2012.05417.x.

[31] Kamjam, M., Sivalingam, P., Deng, Z., Hong, K., 2017. Deep sea actinomycetes and their secondary metabolites. Front. Microbiol. 8. https://doi.org/10.3389/fmicb.2017.00760.

[32] Khamna, S., Yokota, A., Lumyong, S., 2009. Actinomycetes isolated from medicinal plant rhizosphere soils: diversity and screening of antifungal compounds, indole-3-acetic acid and siderophore production. World J. Microbiol. Biotechnol. 25, 649–655. https://doi.org/10.1007/s11274-008-9933-x.

[33] Khamna, S., Yokota, A., Peberdy, J.F., Lumyong, S., 2010. Indole-3-acetic acid production by Streptomyces sp. isolated from some Thai medicinal plant rhizosphere soils. Eurasia J. Biosci. 32, 23–32. https://doi.org/10.5053/ejobios.2010.4.0.4.

[34] Lee, L.H., Chan, K.G., Stach, J., Wellington, E.M.H., Goh, B.H., 2018. Editorial: the search for biological active agent(s) from actinomycetes. Front. Microbiol. 9, 1–4. https://doi.org/10.3389/fmicb.2018.00824.

[35] Lewin, G.R., Carlos, C., Chevrette, M.G., Horn, H.A., McDonald, B.R., Stankey, R.J., Fox, B.G., Currie, C.R., 2016. Evolution and ecology of actinomycetes and their bioenergy applications. Annu. Rev. Microbiol. 70, 235–254. https://doi.org/10.1146/annurev-micro-102215-095748.

[36] Li, F., Liu, Shaowei, Lu, Q., Zheng, H., Osterman, I.A., Lukyanov, D.A., Sergiev, P.V., Dontsova, O.A., Liu, Shuangshuang, Ye, J., Huang, D., Sun, C., 2019. Studies on antibacterial activity and diversity of cultivable actinomycetes isolated from mangrove soil in futian and maoweihai of China. Evid. Based Complement. Altern. Med. 2019. https://doi.org/10.1155/2019/3476567.

[37] Liu, T., Wu, S., Zhang, R., Wang, D., Chen, J., Zhao, J., 2019. Diversity and antimicrobial potential of Actinomycetes isolated from diverse marine sponges along the Beibu Gulf of the South China Sea. FEMS Microbiol. Ecol. 95, 1–10. https://doi.org/10.1093/femsec/fiz089.

[38] Ma, Y., Oliveira, R.S., Freitas, H., Zhang, C., 2016. Biochemical and molecular mechanisms of plant-microbe-metal interactions: relevance for phytoremediation. Front. Plant Sci. 7, 918. https://doi.org/10.3389/fpls.2016.00918.

[39] Maciejewska, M., Adam, D., Martinet, L., Naoˆm´e, A., Całusin´ska, M., Delfosse, P., Carnol, M., Barton, H.A., Hayette, M.P., Smargiasso, N., De Pauw, E., Hanikenne, M., Baurain, D., Rigali, S., 2016. A phenotypic and genotypic analysis of the antimicrobial potential of cultivable Streptomyces isolated from cave moonmilk deposits. Front. Microbiol. 7, 1–19. https://doi.org/10.3389/fmicb.2016.01455.

[40] Marschner H .,2010. Mineral nutrition of higher plants. Academic, London.

[41] Miao, V., Davies, J., 2010. Actinomycetes: the good, the bad, and the ugly.Antonie van Leeuwenhoek Int. J. Gen. Mol. Microbiol. 98, 143–150. https://doi.org/10.1007/s10482-010-9440-6.

[42] Mma, Y., Mfm, E., 2014. Biofertilizers and their role in management of plant parasiticnematodes. A review. E3 J. Biotechnol. Pharm. Res. 5, 1–6.

[43] Mohammed, A., 2020. Influence of Streptomyces sp. Kp109810 on solubilization of inorganic phosphate and growth of maize (Zea mays L.). J. Appl. Plant Prot. 9, 17–24. https://doi.org/10.21608/japp.2020.130644.

[44] Nafis, A., Raklami, A., Bechtaoui, N., El Khalloufi, F., El Alaoui, A., Glick, B.R., Hafidi, M., Kouisni, L., Ouhdouch, Y., Hassani, L., 2019. Actinomycetes from extreme niches in morocco and their plant growth-promoting potentials. Diversity 11, 139. https://doi.org/10.3390/d11080139.

[45] Nandimath, A.P., Karad, D.D., Gupta, S.G., Kharat, A.S., 2017. Consortium inoculum offive thermo-tolerant phosphate

solubilizing actinomycetes for multipurposebiofertilizer preparation. Iran. J. Microbiol. 9, 295–304.

[46] Nath Yadav, A., 2017. Plant growth promoting bacteria: biodiversity and multifunctional attributes for sustainable agriculture. Adv. Biotechnol. Microbiol. 5. https://doi.org/10.19080/aibm.2017.05.555671.

[47] Nett, M., Ikeda, H., Moore, B.S., 2009. Genomic basis for natural product biosynthetic diversity in the actinomycetes. Nat. Prod. Rep. 26, 1362–1384. https://doi.org/10.1215/S0012-7094-44-01176-2.

[48] Ouhdouch, Y., Barakate, M., Finance, C., 2001. Actinomycetes of Moroccan habitats: isolation and screening for antifungal activities. Eur. J. Soil Biol. 37, 69–74. https://doi.org/10.1016/S1164-5563(01)01069-X.

[49] Suh, J.W., 2011. Biological control of anthracnose (Colletotrichum gloeosporioides) in yam by Streptomyces sp.MJM5763. J. Appl. Microbiol. 111, 443–455. https://doi.org/10.1111/j.1365-2672.2011.05048.x.

[50] Palaniyandi, S.A., Yang, S.H., Zhang, L., Suh, J.W., 2013. Effects of actinomycetes on plant disease suppression and growth promotion. Appl. Microbiol. Biotechnol. 97, 9621–9636. https://doi.org/10.1007/s00253-013-5206-1.

[51] Polti, M.A., Aparicio, J.D., Benimeli, C.S., Amoroso, M.J., 2014. Role of Actinomycetes in bioremediation. Microb. Biodegrad. Bioremediat. 270–286. https://doi.org/10.1016/B978-0-12-800021-2.00011-X.

[52] Pratiwi, R.H., Hidayat, I., Hanafi, M., Mangunwardoyo, W., 2020. Isolation and structure elucidation of phenazine derivative from Streptomyces sp. strain UICC B-92 isolated from neesia altissima (malvaceae). Iran. J. Microbiol. 12, 127–137. https://doi.org/10.18502/ijm.v12i2.2618.

[53] Qinyuan, Li, Xiu Chen, Y.J., C.J, 2016. Morphological identification of Actinomycetes.Intech i 13. https://doi.org/10.5772/57353.

[54] Rebets, Y., Bro¨tz, E., Tokovenko, B., Luzhetskyy, A., 2014. Actinomycetes biosynthetic potential: how to bridge in silico and in vivo? J. Ind. Microbiol. Biotechnol. 41, 387–402. https://doi.org/10.1007/s10295-013-1352-9.

[55] Shanmugaiah, V., Nithya, K., Harikrishnan, H., Jayaprakashvel, M.,Balasubramanian, N., 2015. Biocontrol mechanisms of siderophores against bacterial plant pathogens. Sustain. Approaches Control. Plant Pathog. Bact. 167–190. https://doi.org/10.1201/b18892-9.

[56] Shao HB, Chu LY, Jaleel CA, Zhao CX (2008) Waterdeficit stress-induced anatomical changes in higher plants. C R Biol 331:215–225.

[57] Sharma, P., Thakur, D., 2020. Antimicrobial biosynthetic potential and diversity of culturable soil actinomycetes from forest ecosystems of Northeast India. Sci. Rep. 10, 1–18. https://doi.org/10.1038/s41598-020-60968-6.

[58] Sharma, M., Dangi, P., Choudhary, M., 2014. Actinomycetes: Source, Identification, and Their Applications 3, 801–832.

[59] Sharma, M., Tarafdar, A., Ghosh, R., Gopalakrishanan, S., 2017. Biological Control as a Tool for Eco-friendly Management of Plant Pathogens. doi:10.1007/978–981-10–7380-9_8.

[60] Shu, C., Chen, Q., Pi, L., Zhang, D., Panhwar, Q.A., Zhou, E., 2017. Identification and antifungal activity analysis of two biocontrol antagonists to Colletotrichum musae. J. Phytopathol. 165, 554–561. https://doi.org/10.1111/jph.12592.

[61] Sindhu, S.S., Phour, M., Choudhary, S.R., Chaudhary, D., 2014. Nutrient cycling: potassium solubilization by microorganisms and improvement of crop growth. Geomicrobiol. Biogeochem. 39, 199–237. https://doi.org/10.1007/978-3-642-41837-2.[62] Singh, L.S., Sharma, H., Sahoo, D., 2019. Actinomycetes from soil of Lachung, a pristine high altitude region of sikkim himalaya, their antimicrobial potentiality and production of industrially important enzymes. Adv. Microbiol. 09, 750–773. https://doi.org/10.4236/aim.2019.98046.

[62] Soe, K.M., Yamakawa, T., 2013. Evaluation of effective Myanmar Bradyrhizobium strains isolated from Myanmar soybean and effects of coinoculation with Streptomyces griseoflavus P4 for nitrogen fixation. Soil Sci. Plant Nutr. 59, 361–370. https://doi.org/10.1080/00380768.2013.794437.

[63] Soumare, A., Boubekri, K., Lyamlouli, K., Hafidi, M., Ouhdouch, Y., Kouisni, L., 2020a. From isolation of phosphate solubilizing microbes to their formulation and use as biofertilizers: status and needs. Front. Bioeng. Biotechnol. 7, 1–14. https://doi.org/10.3389/fbioe.2019.00425.

[64] Soumare, A., Boubekri, K., Lyamlouli, K., Hafidi, M., Ouhdouch, Y., Kouisni, L., 2020b.Efficacy of phosphate solubilizing Actinomycetes to improve rock phosphate agronomic effectiveness and plant growth promotion. Rhizosphere, 100284. https://doi.org/10.1016/j.rhisph.2020.100284.

[65] Soumare, A., Diedhiou, A.G., Thuita, M., Hafidi, M., Ouhdouch, Y., Gopalakrishnan, S., Kouisni, L., 2020c. Exploiting biological nitrogen fixation: a route towards a sustainable agriculture. Plants 9, 1–22. https://doi.org/10.3390/plants9081011.

[66] Sparks, D.L., Huang, P.M., 1985. Physical chemistry of soil potassium. Potassium Agric.201–276. https://doi.org/10.2134/1985.potassium.c9.

[67] Sreeja, B., Prajapati, K., 2021. Isolation of potassiumsolubilizing actinomycetes from ceramic industry soils. Paripex Indian J. Res. 10 https://doi.org/10.36106/paripex/1510305.

[68] Sreevidya, M., Gopalakrishnan, S., Kudapa, H., Varshney, R.K., 2016. Exploring plant growth-promotion actinomycetes from vermicompost and rhizosphere soil for yield enhancement in chickpea. Braz. J. Microbiol. 47, 85–95. https://doi.org/10.1016/j.bjm.2015.11.030.

[69] Su´arez-Moreno, Z.R., Vinchira-Villarraga, D.M., Vergara-Morales, D.I., Castellanos, L., Ramos, F.A., Guarnaccia, C., Degrassi, G., Venturi, V., Moreno-Sarmiento, N., 2019. Plant-growth promotion and biocontrol properties of three Streptomyces

spp. isolates to control bacterial rice pathogens. Front. Microbiol. 10, 1–17. https://doi.org/10.3389/fmicb.2019.00290.
[70] Subramani, R., Sipkema, D., 2019. Marine rare actinomycetes: a promising source of structurally diverse and unique novel natural products. Mar. Drugs. https://doi.org/10.3390/md17050249.
[71] Subramaniam, G., Arumugam, S., Rajendran, V., 2016. Plant growth promoting actinomycetes: A new avenue for enhancing the productivity and soil fertility of grain legumes. Plant Growth Promoting Actinomycetes: A New Avenue for Enhancing the Productivity and Soil Fertility of Grain Legumes 1–298. doi:10.1007/ 978–981-10–0707-1.
[72] Suleman, P., Al-Musallam, A., Menezes, C.A., 2002. The effect of biofungicide Mycostop on Ceratocystis radicicola, the causal agent of black scorch on date palm. BioControl 47, 207–216. https://doi.org/10.1023/A:1014519726573.
[73] Svenningsen, N.B., Watts-Williams, S.J., Joner, E.J., Battini, F., Efthymiou, A., Cruz-Paredes, C., Nybroe, O., Jakobsen, I., 2018. Suppression of the activity of arbuscular mycorrhizal fungi by the soil microbiota. ISME J. 12, 1296–1307. https://doi.org/10.1038/s41396-018-0059-3.
[74] Syiemiong, D., Jha, D.K., 2019. Search for plant growth promoting actinomycetes from a limestone mining spoil soil in Meghalaya. Res. J. Life Sci. Bioinform. Pharm. Chem. Sci. 5, 1024–1036. https://doi.org/10.26479/2019.0502.77.
[75] Tamreiha, K., Nimaichand, S., Chanu, S.B., Devi, K.A., Lynda, R., Jeeniita, N.,Ningthoujam, D.S., Roy, S.S., 2019. Streptomyces manipurensis MBRL 201(T) aspotential candidate for biocontrol and plant growth promoting agent for rice. IndianJ. Exp. Biol. 57, 741–749.
[76] Thilagam, R., Hemalatha, N., 2019. Plant growth promotion and chilli anthracnose disease suppression ability of rhizosphere soil actinomycetes. J. Appl. Microbiol. 126, 1835–1849. https://doi.org/10.1111/jam.14259.
[77] Tirado, R., Allsopp, M., 2012. Phosphorus in agriculture Problems and solutions.Greenpeace Research Laboratories Technical Report 3–30.
[78] Verma, M., Lal, D., Kaur, Jaspreet, Saxena, A., Kaur, Jasvinder, Anand, S., Lal, R., 2013. Phylogenetic analyses of phylum Actinomycetes based on whole genome sequences. Res. Microbiol. 164, 718–728. https://doi.org/10.1016/j.resmic.2013.04.002.
[79] Viaene, T., Langendries, S., Beirinckx, S., Maes, M., Goormachtig, S., 2016. Streptomyces as a plant's best friend? FEMS Microbiol. Ecol. 92, 1–10. https://doi.org/10.1093/femsec/fiw119.
[80] Vishwakarma, K., Sharma, S., Kumar, V., Upadhyay, N., Kumar, N., Mishra, R.,Yadav, G., Verma, R.K., Tripathi, D.K., 2017. Current scenario of root exudate-mediated plant - microbe interaction and promotion of plant growth. Probiot.Agroecosyst. 349–369.
[81] Wahyudi, A.T., Priyanto, J.A., Afrista, R., Kurniati, D., Astuti, R.I., Akhdiya, A., 2019.Plant growth promoting activity of actinomycetes isolated from soybean rhizosphere. OnLine J. Biol. Sci. 19, 1–8. https://doi.org/10.3844/ojbsci.2019.1.8.
[82] Wang M, Zheng Q, Shen Q, Guo S (2013) The critical role of potassium in plant stress response. Int J Mol Sci 14:7370–7390
[83] Wang, Z., Solanki, M.K., Pang, F., Singh, R.K., Yang, L.T., Li, Y.R., Li, H.B., Zhu, K., Xing, Y.X., 2017. Identification and Efficiency of a Nitrogen-fixing Endophytic Actinomycetesl Strain from Sugarcane. Sugar Tech. 19, 492–500. https://doi.org/10.1007/s12355-016-0498-y.
[84] Wink, J., 2017. Biology and Biotechnology of Actinomycetes. doi:10.1007/978–3-319–60339-1.
[85] Worsley, S.F., Macey, M.C., Newitt, J.T., Patrick, E., Yu, D.W., Wilkinson, B., Murrell, C., Hutchings, M.I., 2019. Investigating the role of exudates in recruiting Streptomyces bacteria to the Arabidopsis thaliana root microbiome. BioRxiv, 532309. https://doi.org/10.1101/532309.
[86] Yadav, N., Nath Yadav, Ajar, 2019. Actinomycetes for sustainable agriculture. J. Appl.Biotechnol. Bioeng. 6, 38–41. https://doi.org/10.15406/jabb.2019.06.00172.