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Review Article

Actinomycetes: Potential Link to Sustainable Agriculture and Environment

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Abstract

Actinomycetes are spore-forming, aerobic bacteria that are gram-positive and possess high guanine-cytosine (57-75%) content in their DNA. They are belonging to Actinomycetales order, which is noted for the development of both substrate and aerial mycelium. These bacteria exhibit true aerial hyphae and have a filamentous structure, resembling fungi. They are among the most prevalent microorganisms found in soil, generating thread-like filaments that contribute to the "earthy" scent associated with freshly turned, healthy soil. Actinomycetes play crucial roles in the cycling of organic matter, suppressing the growth of various plant pathogens in the rhizosphere, and decomposing complex polymer mixtures found in deceased plant, animal, and fungal material, thereby producing many extracellular enzymes that enhance crop production. They significantly aid in biological soil buffering and the biological regulation of soil environments through processes such as nitrogen fixation and the degradation of high molecular weight pollutants like hydrocarbons in contaminated soils. Besides this, actinomycetes can serve as biofertilizers in sustainable agriculture, as they enhance plant growth and soil health through multiple plant growth-promoting features, including the solubilization of phosphorus, potassium, and zinc, the generation of Fe-chelating compounds, production of phytohormones like indole acetic acids, cytokinins, and gibberellins, as well as biological nitrogen fixation. Moreover, actinomycetes do not harm the environment; rather, they bolster long-term soil health by creating and stabilizing compost piles, forming stable humus, and partnering with other soil microorganisms to decompose resistant plant and animal residues, thus preserving the soil's biotic balance by collaborating with nutrient cycling.

Keywords: Actinomycetes; Plant Growth Promotion; Soil Health; Sustainable Agriculture; Biocontrol; Enzymes; Biodegradation; Bioinoculants

Introduction

Actinomycetes are prokaryotic organisms that belong to a subdivision of the gram-positive bacterial phylum [1,2]. Most of these organisms are classified under the taxonomic family Actinobacteridae and the order Actinomycetales. A key feature that sets this group apart is their elevated G+C content, which exceeds 55 mol%. They have a filamentous structure similar to bacteria and generate two forms of branching plant structures: aerial and substrate. The aerial structure is crucial as it contains the spore-producing part of the organism. For this reason, they are categorized as a fungus, which is evident in their name: akitino means ray, and mykes means mushroom/fungus, thus actinomycetes are known as ray fungi as shown in Figure 1. Actinomycetes represent the most diverse category of microorganisms found in nature, and they are recognized for their presence in soil as saprophytes. Geosmin, a foul-smelling compound generated by soil actinomycetes, translates to "earth odor" [3]. This chemical compound is responsible for the strong smell that occurs in the air following a dry spell when it begins to rain. Actinomycetes flourish in the root zones of plants, aiding their growth by decomposing organic materials in the soil or by fixing nitrogen from the atmosphere. Antibiotics are produced that are considered to be effective against plant diseases. *Streptomyces* is the genus that contains the majority of soil-dwelling actinomycetes [4]. They possess the capability to generate a diverse array of secondary metabolites and extracellular enzymes that are economical and advantageous for humanity. Actinomycetes sp. are responsible for over 60% of the biologically active compounds developed for agricultural use, along with other genera such as *Saccharopolyspora, Amycolatopsis, Micromonospora*, and *Actinoplanes*. Actinomycete species produce a range of bioactive compounds, such as macrolides, benzoquinones, aminoglycosides, polyenes, and glycoside antibiotics [5]. Actinomycetes are protecting roots from fungal infections by producing enzymes or by producing antifungal compounds that are break down the plant cytomembrane. They can also break down polymers originating from plants, animals, and microorganisms present in soil and litter [6]. The ways in which actinomycetes safeguard plant roots involve creating associations, displaying parasitic behavior, producing hydrolytic enzymes that work outside of cells, and competing for iron. They may produce a variety of extracellular hydrolytic enzymes such as cellulase, chitinase, and other enzymes [7]. These hydrolytic enzymes initiate the physical breakdown of plant cell walls (FCW). It is believed that siderophores generated by soil actinomycetes, especially those from the genus Streptomyces, help limit the proliferation of phytopathogens by competing for iron in the soils of plant rhizospheres [8].

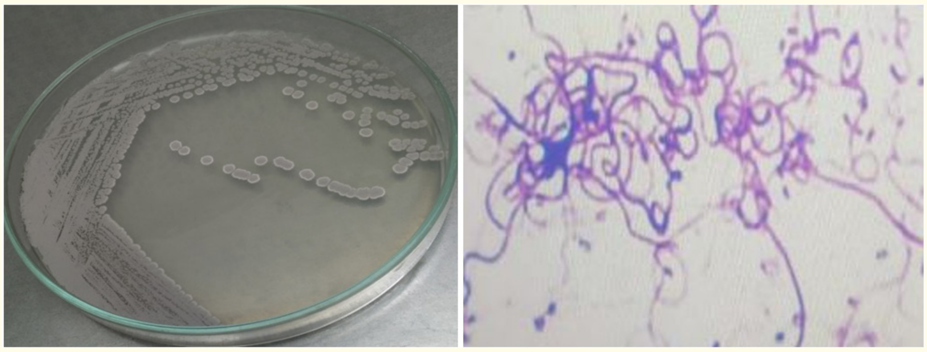

Figure 1: Colony morphology and microscopic feature of Actinomycetes.

Structure of actinomycetes

The actinomycetes spores' spectrum line is studied during germination by the genus actinomycetes [9]. Endospores of the latter species operate similarly to those of eubacteria, with a new wall layer generated inside the cortex of the reproductive structure and extending to form the germ-tube wall. The actinomycete spores studied had a two-layered wall, with the inner layer spreading to create the germ-tube wall [10]. It's unclear if this layer is freshly produced during germination or if it's formed by restructuring of latent spore wall material. The structural modifications that occur during germination of plant spores are widely investigated. The majority of fungus belong to one of the two groups: (I) those in which the germ-tube wall is formed by extending a wall layer already existing inside the latent reproductive structure; (ii) those in which the germ-tube wall is formed by extending a wall layer already present within the dormant reproductive structure wall. Some results are contradictory, as closely related species are said to represent completely distinct teams. This might be due in part to the use of different fixatives, with permanganate yielding lower results than metallic element tetroxide or aldehydes. Even during specimen preparation, associations can cause significant modifications in reproductive structure wall layers. When cultivated on an agar surface, the actinomycetes branch out to produce a network of hyphae that grows both on the surface and beneath the agar. Aerial hyphae are those that are on the surface, whereas substrate hyphae are those that are below the surface. Septa split hyphae into long cells (20 metric linear unit and longer) with several microbe chromosomes, which are not unusual (nucleoids) [11]. These are asexually reproducing aerial hyphae that extend higher than the stratum. Actinomycetes are mostly non-motile, once motility has been established; it is restricted to appendages spores.

Nature and habitat

Actinomycetes are found in large numbers in soil, water sediment, the air, and plants. Actinomycetes are organisms that live in the soil and make thread-like filaments. They can be found in many different places in nature. They are a global cluster of bacteria found in natural ecosystems all over the world [12]. They are generally soil dwellers, however they may be found in a wide range of aquatic systems, as well as sediments recovered from deep ocean depths, including the Mariana Trench [13]. They may be found in harsh conditions, such as Antarctica's cryophilic zone and even desert soil.

Terrestrial environment

Actinomycetes population is greatest in the soil's surface layer and decreases with depth; actinomycetes strains are present at all soil levels. Actinomycetes are the most numerous and widespread soil organisms. They are distributed over the soil, compost, etc. with levels ranging from 10^4 to 10^8 per gram of soil. They are susceptible to acidity/low pH (the ideal pH range is between 6.5 and 8.0) and damp soil conditions [14]. They are mesophilic (25-30 °C) creatures, and only a few species commonly found in compost and manure are thermophilic (55-65 °C) organisms [15].

Fresh water environment

In water lakes, actinomycetes are abundant. They grow well at 60 °C and are typically found in garbage [27]. From fresh environments, representatives of the genera *Actinoplanes, Micromonospora, Rhodococcus,* actinomycetes, and therefore the endospore-forming thermoactinomycetes have been identified [16]. The majority of those actinomycetes are most likely washed in from the land and gathered in a new habitat. Actinoplanes have been found on allochthonous leaf litter washed up on the lakeshore and on twigs submerged in streams. *Micromonospora* members constitute a really native group of microbial residents of inner lake waters and bottom deposits. *Micromonospora* spores will be survived into streams, rivers, and lakes will persist as latent propagules [17].

Marine environment

Actinomycetes were thought to exist in marine environments owing to soil pollution or their presence on algal debris floating on the sea's surface [18]. Because there are no obvious morphological or chemical chemistry differences between the marine and terrestrial isolates, the actinomycetes may have evolved on land but were adapted to the salt level of ocean water. The actinomycetes spores can be carried from land to sea by rain or rivers. Deep sediments, on the other hand, contain bound native actinomycetes. Furthermore, in most quantities of actinomycetes from near-shore sediments in both shallow and deep sampling locations, a bimodal distribution in relevant depth was observed [19]. As a result, marine-derived actinomycetes are thought to have arisen in terrestrial habitats.

Extreme environments

Actinomycetes are found in harsh environments. Alkalophilic actinomycetes (the prevalent species are *Streptomyces* and *Nocardiopsis)* live in basic soils (pH 10-12) near mineral springs. Acidophilic actinomycetes isolated from acidic forest and humate soils, primarily actinomycetes and *Micromonospora*, obligatory psychrophilic actinomycetes isolated from acidic forest and humate soils [20] with optimal growth temperature 9-12 °C and not growing at temperature greater than 18°C Thermophilic actinomycete spp. were extracted from silt in the same way that meteor crater water samples were. *Microbispora, Nocardia, Microtetraspora, Amycolaptosis, Actinomadura,* and *Saccharothrix* were among the few thermo tolerant actinomycetes identified from dry soils of the Mojave Desert [21].

Plant growth promotion by actinomycetes

Plant growth promotion is one of the most important features of microorganisms, along with actinomycetess. Actinomycetes live in the rhizosphere of plants and have a wide range of biological and physiological effects on plants, as well as a protective function against diseases. *Micromonospora, Eubacterium, Frankia, Mycobacterium*, and *Rhodococcus* genera have been implicated in plant growth promotion, either directly (production of phytohormones) or indirectly (production of cell-wall-degrading enzymes) [22]. These actinomycetes produced phytohormones (auxin) and helped plants grow and develop under stressful situations. A variety of additional species are reportable as plant root colonizers while actinomycetes are reportable as plant growth boosters. Actinomycete strains have antagonistic action against a variety of rice flora diseases, as well as the capacity to solubilize phosphate and produce chitinase [23]. Different strains of actinomycetes promote plant growth by enhancing mycorrhiza development. Actinomycetes strains have been shown to produce siderophore, which is another important factor in plant growth promotion.

Phosphate solubilization

Phosphate solubilizes are the most important part of an environmentally friendly way to help plants grow [24]. But the biggest problem with phosphate-solubilizing microorganisms is that they can only be used in very specific ways because of how the soil is made. This means that research into them is still in its early stages. To understand how phosphates get dissolved in water, it is important to know how they are found in the soil and how microorganisms can make them available to plants. Healthy plant performance requires phosphorus (P) that is involved in processes ranging from the metabolism of cellular energy to the inheritance of genetic traits between generations. Most of the inorganic phosphate in the soil is in the form of mineral phosphate. Depending on the soil's pH, the phosphate is either tricalcium phosphate or iron phosphate. Small-molecular-weight organic acids could dissolve these phosphates in a laboratory setting [25]. Soil becomes more acidic when organic acids do their job. By replacing the cation that was bound to phosphate with H+, soil acidification caused the monovalent phosphate anion to be released from the mineral phosphate. It has been shown that microorganisms use this method by releasing organic acids when they oxidize organic carbon sources. But actinomycetes are rarely talked about in terms of their role in making organic acids, even though they are the main source of many bioactive substances made by microorganisms. Production of organic acid depends on the type of species of actinomycetes. *M. endolithica* that produce variety of organic acids such as malic acid, lactic acid, oxalic acid, acetic acid and gluconic acid. Some actinomycetes, including *Streptomyces, Microbacterium, Thermobifida, Angustibacter, Kocuria, Isoptericola,* and others, have the characteristic of phosphate solubilization. Microorganisms use a different way to break down (mineralize) organic phosphorus, which is the most common form of phosphate in soil. Soil microbes make enzymes like phosphatases and phytases that break down organic phosphorus compounds into soluble inorganic phosphates this process is called phosphorylation [26]. The nonspecific acid phosphates that react with the phosphoester or phosphoanhydride linkage in the organic compound are the most important of these enzymes. People often mix up the activity of microbial acid phosphatase with the phosphates made by plant roots. But it has been said that phosphates that come from microorganisms bond better with organophosphate compounds than phosphates that come from plants [27]. Alkaline phosphates are a type of phosphates enzyme that is made by microbes in both alkaline and neutral soil. Phytate is another way that organic phosphate gets into the soil. It is a form of phosphorus that is stored in the seeds and pollen of plants. However, it is not very useful to plants as a source of soluble phosphorus through the breakdown of phytate. This problem is fixed by microorganisms that break down phytates. This is an important part of making more soluble phosphorus available in the soil for plant growth. So, to make the right phosphate-solving microbial bioinoculant for a certain type of soil, you will need to know a little bit about the soil and how the microbes work. Among the seventeen nutrients that are necessary for crop development and growth of the plant, potassium (K) is known as the third major nutrient. Nevertheless, only 1-2 % of the significant potassium resource in the soil is directly accessible to plants; the other 90-98 % is in the form of non-exchangeable silicate minerals like feldspar and mica. This clarifies the conundrum of soil being both K-rich and K-deficient. Biological methods have been proposed to take use of this K reservoir and make it available for crop development. The Figure 2. Summarizes the P and K solubilization by Actinomycetes and their plant growth promoting attributes.

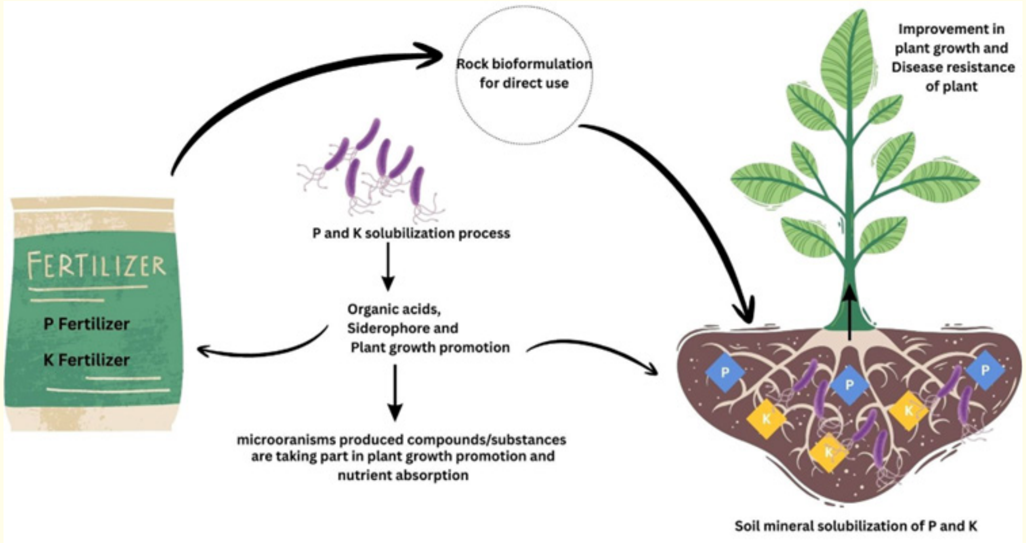

Figure 2: P and K solubilization by actinomycetes.

Phytohormones production

Throughout its existence, a plant creates hormones to control its growth and metabolism in response to a variety of nonlethal environmental stimuli. Each hormone has many effects, which vary according to the developmental stage of the plant and hormone concentration at the location of action. A variety of signaling cascades involving many genes have been identified as the regulation mechanisms of the numerous phytohormones [28]. There will be several growth-limiting environmental circumstances that have a negative impact on plant development, as well as an excessive release of phytohormones; there are so many damaging impacts on the soil and environment, thus resulting in leaf withering and plant mortality. The most prevalent is the synthesis of ethylene in response to a stressful environment in plants. Under in vitro circumstances, phytohormone-producing bacteria, particularly actinomycetes, control the hormonal levels necessary for plant development and, by extension, their reactions to environmental stress. The precise methods via which these bacteria regulate plant metabolism are still not fully known. Through the release of plant hormones, it was shown that certain phytopathogens, particularly Agrobacterium, appear to capture plant cells for nutrient production required to their development [29]. Phytohormone synthesis is how bacteria, specifically PGPR, exert their positive influence on plants despite contradictory reports. The most significant phytohormone is indole-3-acetic acid (IAA) [30].

Nutrient mobilization

Generally, Actinomycetes are producing various enzymes and compounds due to this nutrient mobilizing occurred in soil which is shown in figure 3. The potential function of actinomycetes in nutrient mobilization in several plant species, in addition to biocontrol and growth promotion, has been described by studies. Several actinomycete species are found from potassium-rich soil samples and proven to be capable of mobilizing potassium from cocco agricultural waste [31]. By mobilizing bound potassium from onion Cocco pods, actinomycetes promote plant development. Hence, actinomycetes with onion Cocco pods can be utilized as a biofertilizer. In addition, the function of actinomycetes, members of the genus Streptomyces, in zinc solubilization was documented. Actinomycetes were colonized alongside mycorrhizal fungi. This demonstrated the remarkable capacity of actinomycetes to share the highly competitive habitat, rhizosphere, without interfering with the plant growth-promoting characteristics.

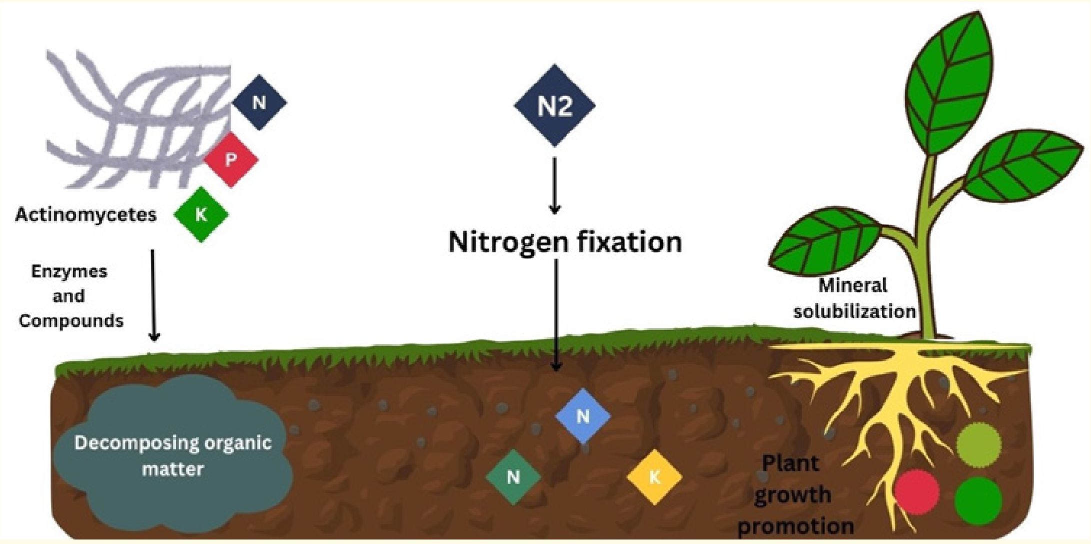

Figure 3: Nutrient mobilizing by actinomycetes in soil.

Role of actinomycetes in soil and plant health

In some ways, soil around the world are similar to a pile of inert rock particles, but one of the most important factors is that they require a population of microorganisms to live among them, which derives its energy from the oxidizing organic residues left behind by the plants growing on the soil. Within the tip, plants are growing on soil that is rich in microbial activity, with microorganisms often oxidizing dead plant remnants and passing on the element and mineral compounds that the plants require for growth [32]. Soil microorganisms are often divided into three categories: microorganisms, actinomycetes, and fungus. *Streptomyces* and *Micromonospora* are the two most common genera of actinomycetes. They normally have a lot of branching hyphae as they're growing, which split into spores, either by the tip of the hyphae producing one or two spores [33]. Polysaccharide, hemicelluloses, proteins, and polymer are among the carbon and nitrogen compounds they hope to utilize. Most members are aerobics, with a few having a limited capacity to overcome nitrates. They also appear to move under pastures and may be the dominating microorganisms in the grassland surface layers.

Nitrogen fixation

Microorganisms play a critical role in the use of a variety of agricultural wastes. Microorganisms are important in agricultural soils because they contribute to the carbon cycle through photosynthesis and decomposition. Actinomycetes are very good in breaking down tough substances because there are so many microorganisms living in the environment that are required decomposers [34]. Because land management impacts nutrient levels, it has an impact on the organization of microorganism communities, shifting the dominance of decomposers from microorganisms to plant life. Actinomycetes are frequently associated with a variety of non-leguminous plants and fix atmospheric nitrogen, which is then available to both the host and other plants in the vicinity. Nitrogen may be an essential ingredient for all living things. Plants provide us with nitrogen either directly or indirectly. Plants cannot utilize N in its vaporous condition, despite the fact that it makes up around 79 percent of our atmosphere. The first stage will be to mount the nitrogen (N) or mix it with ammonia (NH_3) or nitrate (NO_3). The *Frankia* actinobacteria family is the most common microbe discovered in natural nitrogen fixers [35]. There are dependent linkages that indicate that 15% of the world's nitrogen is naturally mounted. They are mostly actinomycetes belonging to the *Frankia* family. Plants that are reliant on Frankia are known as actinorhizal plants. It may be capable of giving the entire N that the host plant requires; also, they're the most important N-fixing connections in many parts of the world, and they'll only grow more important when global climate change occurs.

Decomposition of organic matters

Actinomycetes are the most important group of soil microorganisms for breaking down organic matter in the environment by making enzymes that break down water. Actinomycetes is a decomposer that specializes in breaking down strong polysaccharides and polymers like those found in wood, paper, and insect exoskeletons (chitin). This breaks down the nutrients so that the plants can use them. During the composting process, it is mostly thermophilic and thermo tolerant actinomycetes that break down the organic matter at higher temperatures [36]. In the beginning of the composting process, when there is a lot of microbial activity, the organic matter heats itself. In composting, the temperature will be very high, which makes it easy to kill microorganisms that cause disease. Actinomycetes mostly live in an aerobic way, which means they need oxygen to live. Most of the time, Actinomycetes grow much more slowly than other microorganisms or fungi on modern substrates. The places where thermophilic actinomycetes live on their own are silos, corn mills, air conditioning systems, and closed stables.

Siderophore production

Iron may be an important nutrient for almost all living things, including plants and microorganisms in the soil. In an aerobic environment, iron is mostly found as Fe^{3+} in insoluble hydroxides [37]. When siderophores combine with Fe^{3+}, plasma membrane receptors pick up on this. This could be a way to make it easier to add the shape to the cell. Once inside the cell, Fe^{3+} ions are broken down into Fe^{2+}, which can then be used in different biological processes. This makes it hard for plants and microorganisms to get to. Siderophores are iron chelators with a low mass and a high affinity for iron. They are made by some microorganisms and actinomycetes to get rid of metal iron by making ferric-siderophore complexes that are moved into the cells by transport mechanisms [38]. Streptomyces species are known for making hydroxamate-type siderophores, which stop phytopathogens from spreading by limiting the amount of iron in the rhizosphere. Microbial siderophores can also be used by plants to get iron.

IAA production

IAA is the primary plant hormone that regulates growth and biological processes such as organic elongation, tissue differentiation, top dominance, and reactions to light, gravity, and pathogens [39]. The roots are the most vulnerable to changes in IAA levels. The synthesis of IAA can be induced by six different actinomycete species in the presence of tryptophan organic compound, with indole-3-acetamide as the main pathway [40] as *S. violaceus* and *S. exfolitus* catabolized indole-3-ethanamide (IAM), indole-3-lactic acid (ILA), indole-3-grain alcohol (IEt), and indole-3-acetaldehyde Encapsulation of microbic cells for soil application has a number of benefits, including soil application, reduced off-site drifting, and cell protection from environmental stress. Furthermore, they have a high cell loading capacity, high cell viability retention, and an increased rate of microbial product generation, as well as acting as a reservoir that may unharness the microbe at a steady and consistent rate Because of their thin nature, actinomycetes may colonize dry soil for lengthy periods of time as resting arthrospores that germinate in the presence of foreign substrates. So far, the potential of encapsulated actinomycetes for IAA assembly has not been completely explored, nor has it been used in field circumstances to any significant amount. They also have an indirect effect by influencing the activity of the native soil microflora. Salinity, an unfavorable soil pH scale, extremes in temperature, significant metal toxicity, and biocides are some of the common environmental challenges that organisms in the soil endure. IAA is a plant hormone and a kind of auxin that is active. It plays an important role in plant growth by stimulating the expansion of the radicular system, the formation of lateral roots, and the divisions of the top plant tissue, all of which result in root elongation. This increases the amount of soil nutrients available to the plant [41]. IAA is the principal internal secretion responsible for promoting plant development through organic processes related with diazotrophic microbe activity. In actinobacteria, the assembly of IAA has been extensively explored. IAA will operate as an angiosperm regulator of actinomycete atroolivacezlz reproductive structure germination and may be involved in actinobacteria differentiation [42].

Actinomycetes as biocontrol tools

Biological management is described as a method for managing insect, weed, and disease natural enemies [43]. Plant pests (harmful insects, parasitic weeds, and diseases) are among the most important agents causing substantial losses and damage to agricultural goods [44]. Currently, varieties of strategies are employed to control and manage plant pests. Fungi, bacteria, viruses, and nematodes are plant diseases that cause significant harm to agricultural plants. Crop losses pose a severe danger to food supply, with an alarming 27 to 42 percent loss in global food production attributable to plant diseases caused by plant pathogens [45] which would have been quadrupled if no disease control strategies were to be used. Principally, chemical pesticides are used to control several plant diseases. Nonetheless, the widespread misuse of pesticides in agriculture has been a subject of public concern and investigation due to the possible adverse consequences on the environment and organisms [46]. Thus, a variety of chemical pesticides are now in great demand. *Actinomyces griseoviridis* is a prime example of an actinomycete-based biocontrol agent. It has been shown to be antagonistic to a variety of plant diseases, including is utilized in the root dipping or growth nutrition therapy of cut flowers, potted plants, greenhouse cucumbers, and several veggies [47]. Mycostop is a bio-fungicide whose active component is *S. griseoviridis* [48].

Actinomycetes enzymes

Actinomycetes produce diverse enzymes that degrade complex organic substances in soil or sediments, including peptidases, cellulases, amylases, gelatinases, lectinases, catalases, chitinases, and ureases. Actinomycetes are the principal decomposers of decomposing organic materials, especially lignocellulose wastes. They have the extraordinary capacity to supply enzymes such as cellulase, xylanase, polymer oxidase, and chitinase that can commence plant biomass decomposition and convert it into a form that secondary decomposers can utilize. Advanced nutrients are transformed into the simplest mineral forms that work as natural fertilizers and promote the physiological condition of plants. Enzyme has significant importance in biotechnological applications such as the food industry, fermentation, and textile to paper industries [49]. Amylases are exoenzymes that are released by cells to aid in the digestion of living organisms. It is reported that actinomycetes are polysaccharide makers. An abundance of actinomycetes produces enzyme. Lipases have several uses in the detergent, food, oleo chemical, diagnostic, and pharmaceutical sectors [50]. Actinomycetes encompass a huge importance since they possess a capability to provide a spread of living thing hydrolytic enzymes [51]. Actinomycetes and Bacilli are the most common microorganisms that produce base-forming proteases. *Streptomyces* are renowned for their ability to release numerous proteases in medium [52]. Actinomycetes have been revealed to be an excellent source of L-asparaginase. Actinomycetes isolated from rhizosphere soils, such as *Streptomycesgriseus, S. karnatakensis, S. albidoflavus*, and *Nocardia sp.,* are capable of producing L-asparaginase accelerator. L-Cancer drugs are utilized as a therapeutic agent in the treatment of human malignancies, namely acute lymphocytic leukemia. Keratin-degrading and antibiotic-producing actinomycetes such as *Saccharomonospora, Nocardioides, Nocardiopsis*, and *Nonomuraea* have the ability to convert chicken farm feather waste into odourless and pathogen-free biofertilizer by composting [53,54], eubacterium cellulases which are inducible living enzymes produced during their growth on plastics. Thus, the introduction of cellulolytic microorganisms may be a useful microbiological tool for the recovery of bioenergy from degraded polysaccharide. Cellulolytic microorganisms have attracted significant interest due to their wide applicability in a variety of industrial processes, including pulp and paper, textile, laundry, biofuel production, food-feed business, and agriculture [55]. *Actinomycete scabrisporus, actinomycete sparsogenes, actinomycete misakiensis, actinomycete cirratus*, and *actinomycete alboniger* provide a wide range of accelerator activities, and these isolates may also operate as antibiotics and enzyme-producing bacteria [56].

Actinomycetes in biocorrosion Corrosion

It is a primary cause of pipe failure and high preservation costs in gas pipelines. Biocorrosion is defined as caustic damage caused by microorganisms' direct or indirect activity. Diverse spectrums of microorganisms survive in most, if not all, boring regions, and are represented by water injection plants, lubricant, and live reservoir cores. Antimicrobial material (AMS) produced by a *Streptomyces* strain that has action in biofilm formation and biocorrosion against aerobic bacteria, pumilus and sulfate-reducing bacteria [57]. Previously, *S. lunalinharesii* was identified as a generator of bioactive substances against phytopathogenic microorganisms and fungi. The antibacterial action was seen throughout a wide range of hydrogen ion concentrations, and after treatment with numerous chemicals and heat, but not with peptidase K and enzyme [58]. The antimicrobial material has been reported to be promising for application in oil producing facilities due to its stability in the presence of several chemicals and throughout a wide range of temperature and hydrogen ion concentration values.

Actinomycetes as agents of biodegradation/bioremediation

Pesticides with various chemical structures, such as organochlorines, s-triazines, triazinones, carbamates, organophosphates, organophosphonates, acetanilides, and sulfonylureas, are also degraded by actinomycetes. Indigenous soil actinomycetes are suspected of causing weed herbicide breakdown. Diuron, a phenylurea derivative, is widely employed as a weed biocontrol agent in non-crop regions and, at low concentrations, on crops such as cotton, pineapple, citrus, and sugar cane [59]. *In vitro*, the chosen actinomycetes showed up to 37 percent weed killer breakdown in seven days after being treated with Diuron. Actinomycetes that degrade rubber are common in nature due to natural rubber deterioration [60] as actinomycetes have exclusive access to carbon. Actinomycetes have several properties that make them good candidates for bioremediation of soils contaminated with various organic pollutants. They play an important role in the use of organic carbon and can even breakdown a variety of sophisticated polymers. *Streptomyces* is an important player in the hydrocarbon degradation process. By producing polysaccharide- and hemicellulose-degrading enzymes as well as generating thing peroxides, several strains may solubilize polymer and breakdown lignin-related substances. Different total chemicals produced by various actinomycetes strains are assisting in the isolation and screening of new strains to discover novel compounds [61]. They are the main cluster among the degraders in some polluted areas. These animals are adaptable enough to thrive in oily environments. As a result, these microbes will be used in bioremediation to remove oil contaminants. Around 23,000 bioactive secondary metabolites are claimed to be created by microbes, with over 10,000 of those chemicals synthesized by various actinomycetes species [62].

Actinomycetes as Bio-inoculants

Regular agricultural techniques, although potentially beneficial in supplying the food demands of a growing global population, have also resulted in an increase in dependency on chemical fertilizers and pesticides. The major difficulty for the scientific community is the environmental contamination, which has become a possible hazard for the environmental community as a result of rapid population, manufacturing, and urbanization expansion. Things might be due to the ongoing loss of agricultural land, which affects crop output at the same time. Furthermore, there are a variety of reasons for the decline in agricultural fertility; nonetheless, pests and diseases have a significant role in crop losses. Crop output losses due to the virus have been estimated to be between 20 and 40% across the globe [63]. Plant microorganisms not only reduce agricultural productivity, but they also degrade food quality by producing a variety of poisons [64]. Crop losses due to pests and viruses in the environment are still a constant, and pesticide usage on a daily basis poses major challenges and threats to human health. Due to growing disease resistance, a number of chemical pesticides may not appear to be effective or need overdosing for many results, necessitating a high-cost investment relative to projected financial return for farmers. Fungicides and pesticides can help manage crop diseases to some extent, but the cost is high, and with human health and the environment as top priorities, using microorganisms as biological management agents is the best option. Plant-friendly microorganisms thrive in the soil around the roots (rhizosphere) and among the healthy plant parts (endophytic). The use of microbe-based biopesticides for property agriculture has exploded recently all over the world. Useful microorganisms and fungi, as well as arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria, make up bio-fertilizers and biopesticides (PGPR). Bio-inoculants have the capacity to maintain soil conditions by using all sorts of micro- and macronutrients via biological processes, phosphate and metal solubilization and soil organic matter biodegradation. Actinomycete species are saprophytic bacteria that degrade organic materials in soil and water, notably biopolymers such as lignocellulose, starch, and polyose [65]. Some actinomycetes have unique biological properties, such as mycelia proliferation and monogenesis. They have the ability to biosynthesize a wide variety of antibacterial chemicals. Actinomycetes spp. are well-known as a major source of bioactive natural products, which are mostly used in agrochemicals and prescription medications [66]. Streptomyces produces approximately 75% of economically useful antibiotics. Furthermore, a number of Streptomyces species have come under examination for their capacity to produce a variety of secondary metabolites as well as bioactive substances [67]. *Phytophthora capsici, Fusarium oxysporum f. sp. cubense, Fusarium oxysporum f. sp. ciceri, Sclerotium rolfsii, Alternaria alternata, Phomopsis archeri*, and *Rhizoctonia solani* are all examples of plant morbific fungi that are commonly used as antifungal biocontrol agents. Actinomycetes have been used as plant growth promoters, biocontrol agents, biopesticides, and antifungal agents. Antibiotics such as antibiotic, nystatin, antibiotic medication, and Garamycin are produced by actinomycetes. Urauchimycin is an antibiotic that inhibits lepton flow throughout the mitochondrial metabolic chain, making it an antifungal antibiotic against plant pathogens.

Application of actinomycetes as bio-inoculants

Against plant life plant pathogens

Fungal plant microorganisms do severe harm to both the quantity and quality of food production. Chemical treatment is used to manage plant diseases; nevertheless, these chemicals have a harmful influence on the environment and human health. Since a result, microbe-based technology has garnered attention in order to reduce the use of pesticides as they function for both biocontrol and plant growth promotion. *Streptomyces violaceusniger* strain YCED-9, an antifungal biocontrol agent, contains three antimicrobial chemicals (guanidyl fungin *A, nigericin* [68] and geldanamycin that are effective against *Pythium* and the *Phytophthora spp*. Oligomycins A and C are macrolide antibiotics produced by *Streptomyces diastaticus* that have a significant antifungal activity against *Aspergillus niger, Aspergillus alternative,* and *Botrytis cinerea* [69]. Aside from antibiotic molecule synthesis, bio-inoculants using actinomycetes as active components are employed for disease control. Cells of *actinomycete griseoviridis* are used to treat carnation sickness and cucumber plant disease, and it has been employed in greenhouse production to protect flowers from diseases. Actinovate®, a *S. lydicus* biocontrol product licensed with AgBio in the United States of America, has been recommended for a wide range of habitats ranging from greenhouses to field conditions. It has been reported that *S. lydicus* WYEC 108 (MicroPlus®) provides sickness suppression against mildew and numerous other root decay fungi.

Against microorganism plant pathogens

Actinomycetes produce a diverse range of antibacterial chemicals, which are beneficial for dominating microorganism infections in a variety of plants. *Streptomyces sp*. Strain OE7 reduced the severity of symptoms induced by *Pectobacterium carotovorum* and *Pectobacterium atrosepticum*, the causal agents of potato plant disease, by 65–94%. Antimicrobial activity of phenyl acetic acid and metallic element phenyl acetate derived from Streptomyces humidus against plant diseases and microorganism pathogens [70] metabolites inhibit *Saccharomyces cerevisiae* and *Pseudomonas syringae pv. Syringae*. *Streptomyces sp.* strain JJ45 has antibiotic action against the plant pathogen *Xanthomonas campestris pv.* as well as a repressor chemical known as alpha-lsorbofuranose (3-->2)-beta-D-altrofuranose.

Advantages and drawbacks of Actinomycetes as Bio-inoculants

Actinomycetes bio-inoculants and metabolites are existing chemicals that suppress microorganisms and pests through non-toxic processes [71]. The beneficial effects of actinomycetes and their metabolites have long been recognized; thus, agro-active antibiotics and compounds have recently gained economic relevance in the market. Recently, given the potential of actinomycetes and their frequency and domination within the agro-environment, which might be regarded to promote actinomycetes inoculants, when the full safety analysis was performed.

Advantages

- It only impacts a single microbe or, in rare situations, a group of organisms.
- It decomposes fast, resulting in smaller exposures and, for the most part, no environmental problems.
- It encourages mycorrhizal colonization.
- It regulates the soil nutrient cycle and adds to the organic N and P residual pool, minimizing N leach loss and P fixation, while also providing micronutrients to the plant to enhance metabolic activities.
- It feeds and encourages the growth of beneficial insects, pests, and earthworms.
- They boost plant defense and, conversely, soil immunity to keep harmful pests at bay.
- Plant diseases, parasites, and soil-borne illnesses.

Disadvantages

- The rate of proliferation is slower than that of other microorganism inoculants.
- Preparation and application are relatively dissimilar and susceptible to environmental conditions.
- The success rate is not the same as chemical plant food.
- A lower temperature is necessary for old usage storage.

Critical analysis and future perspectives

Actinomycetes have a lot of promise for agriculture since they can dissolve nutrients, make phytohormones, and stop diseases from spreading. However, much of the research that has been done on them has been done in labs or greenhouses. Their performance in field conditions is frequently uneven, owing to changes in soil type, meteorological circumstances, and crop species. Furthermore, actinomycetes' sluggish growth rate and susceptibility to environmental variations limit their widespread use as bio-inoculants. Another problem is the formulation and storage of actinomycete-based products, as preserving viability and efficacy over long periods of time is more challenging than with typical microbial inoculants. These limitations highlight the need for care when interpreting existing data, since many effectiveness claims remain context-dependent. Further on, multi-location field trials should be the main focus of future research in order to confirm the effectiveness of promising strains in various agroclimatic zones. Actinomycetes and other helpful microorganisms like mycorrhizae and bacteria that promote plant growth can be combined in consortia-based formulations to improve soil stability and offer synergistic effects. Developments in metabolic engineering, synthetic biology, and omics technologies may also aid in the identification of genes resistant to stress and in the customisation of strains with improved biocontrol and characteristics that promote plant development. Additionally, encouraging industry-academia partnerships will be crucial to overcoming the difficulties associated with the formulation, large-scale manufacture, and commercialisation of products based on actinomycetes. Actinomycetes can be positioned as essential instruments for environmentally friendly and sustainable crop production in the long run by incorporating them into climate-smart agriculture and circular bioeconomy plans.

Conclusion

Actinomycetes play a pivotal role in sustainable agriculture by fixing atmospheric nitrogen, decomposing organic matter through hydrolytic enzymes, solubilizing phosphates, producing phytohormones, and degrading harmful pesticides without polluting the environment. Their potential as bio-inoculants against a wide range of phytopathogens highlights them as strong alternatives to chemical fertilizers and pesticides. To translate this potential into practice, actinomycete-based formulations should be integrated into crop management systems, preferably in combination with organic amendments and mycorrhizal fungi for enhanced stability and performance. The development of multi-strain consortia can provide broader effectiveness than single strains, while large-scale field trials across diverse agro-climatic regions are essential to validate their efficiency under real farming conditions. Furthermore, molecular studies targeting stress-resistance traits and stronger collaborations between academia and industry are recommended to accelerate product development and commercialization. With these targeted efforts, actinomycetes can evolve from promising soil microbes into reliable, eco-friendly solutions that support climate-smart and resilient agriculture.

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Disclosure Statement

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