Chapter

Application of Actinobacteria in Agriculture, Nanotechnology, and Bioremediation

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Abstract

"Actinobacteria" are of significant economic value to mankind since agriculture and forestry depend on their soil system contribution. The organic stuff of deceased creatures is broken down into soil, and plants are able to take the molecule up again. Actinobacteria can be used for sustainable agriculture as biofertilizers for the improvement of plant growth or soil health by promoting different plant growth attributes, such as phosphorus and potassium solubilization, production of iron-chelating compounds, phytohormones, and biological nitrogen attachment even under the circumstances of natural and abiotic stress. Nanotechnology has received considerable interest in recent years due to its predicted impacts on several key fields such as health, energy, electronics, and the space industries. Actinobacterial biosynthesis of nanoparticles is a dependable, environmentally benign, and significant element toward green chemistry, which links together microbial biotechnology and nanobiology. Actinobacterial-produced antibiotics are common in nearly all of the medical treatments, and they are also recognized to aid in the biosynthesis of excellent surface and size properties of nanoparticles. Bioremediation using microorganisms is relatively safe and more efficient. Actinobacteria use carbon toxins to synthesize economically viable antibiotics, enzymes, and proteins as well. These bacteria are the leading microbial phyla that are beneficial for deterioration and transformation of organic and metal substrates.

Keywords: Actinobacteria, *Streptomyces*, PGPR, agriculture, nanoparticles, bioremediation

1. Introduction

One of the largest taxonomic groups of bacteria, Actinobacteria, are generally gram-positive with high Guanine + Cytosine (G + C) content (usually around 70%), a common marker in bacterial systematics [1, 2]. They are unicellular, filamentous, spore-forming, motile, or nonmotile and can be aerobic or anaerobic in nature [3]. The morphological structure ranges from coccoid (*Micrococcus*) and rod-coccoid (*Arthrobacter*) to fragmenting hyphal forms

(*Nocardia*) and branched mycelium (*Streptomyces*) [4]. In culture media, actinobacterial colonies have a powdery consistency and adhere tightly to the agar surface, forming hyphae and conidia/sporangia-like fungi on (aerial mycelium) or under (substrate mycelium) the agar surface [2, 5]. Found in a plethora of environment, including terrestrial and aquatic (both marine and freshwater), they share features of both the bacteria (chromosomes organized in a nucleoid and cell wall made of peptidoglycan) as well as fungi (presence of mycelium) [1, 2, 6]. Actinobacteria possess high ecological significance with an immense ability to produce organic acids, fix nitrogen from the atmosphere, and impart an essential role in the decomposition of organic compounds including cellulose and chitin, thus contributing to organic matter turnover and the carbon cycle. This further renews the supply of nutrients in the soil and forms humus [2, 3]. They play a crucial role not only in agriculture but also in the clinical and pharmaceutical industry [7]. Antibiotics, antifungals, enzymes, enzyme inhibitors, antivirals, antioxidants, anticholesterol, antiprotozoal, anticancer, and immunosuppressant are few of the beneficial secondary metabolites with therapeutic implications produced by Actinobacteria [1, 6, 7]. Some of the important genera of Actinobacteria found in soil are *Actinoplanes*, *Micromonospora*, *Nocardia*, *Streptomyces*, and *Streptosporangium* [2], and found as plant or animal pathogens are *Corynebacterium*, *Mycobacterium*, or *Nocardi*a [1].

2. Types of Actinobacteria

Actinobacteria, along with normal environments, can thrive in extreme environments like acidic/alkaline pH, low/high temperatures, high salt concentration, high level of radiation, low moisture content, and nutrients [2]. Based on the above environmental conditions, the different types of Actinobacteria along with their ecological significance have been summarized in **Table 1**.

Considering capabilities of Actinobacteria (**Table 1**), they can potentially be exploited as a candidate for agriculture and environmental biotechnology.

Types of Actinobacteria	Ecological significance	Important genera	References
Thermophilic	• Used in composting, antimicrobial activity, and plant growth promotion and in the production of polyester-hydrolyzing enzymes. • Responsible for causing severe respiratory diseases such as Farmer's lung and bagassosis.	• *Amycolatopsis, Cellulosimicrobium, Micrococcus, Micromonospora, Planomonospora, Saccharopolyspora, Streptomyces, Thermobifida, and Thermomonospora.* • *Saccharopolyspora rectivirgula, S. viridis, Thermoactinomyces viridis, and T. vulgaris.*	[4, 5]
Acidophilic	• Exhibit strong antagonistic effect toward multiple fungal root pathogens (for example, inhibit the rice pathogenic fungi *Fusarium moniliforme* and *Rhizoctonia solani*), phosphate solubilization activity, and produce siderophores.	• *Actinospica*, *Catenulispora*, and *Streptomyces acidiphilus*.	[8]

Types of Actinobacteria	Ecological significance	Important genera	References
Halophilic	• Produce vital metabolites and enzymes (amylase, cellulase, lipase, and protease) with respect to stress response.	• *Actinomycete*, *Actinokineospora*, *Actinopolyspora*, *Dactylosporangium*, *Halothermothrix orenii*, *Marinophilus*, *Microbacterium*, *Micrococcus*, *Microtetraspora*, *Mycobacterium*, *Nocardiopsis*, *Rhodococcus*, *Saccharopolyspora*, *Salinispora*, *Streptomyces*, and *Streptoverticillium*.	[9]
Endophytic	• Protect and guard the host plants against insects and diseases. • Produce secondary metabolites such as alkaloids, polyketides, terpenes, and terpenoids benzopyrones, quinones, peptides and fatty acids derivatives, which are of therapeutic importance.	• *Actinomadura, Actinopolyspora, Brevibacterium, Kibdelosporangium, Nocardioides,* and *Streptomyces.* • *Aeromicrobium, Kitasatospora, Microbispora, Micromonospora, Nocardia caishijiensis,* and *Pseudonocardia, carboxydivorans, Streptomyces*, and *Verrucosispora maris*.	[2, 6]
Symbiotic	• Form nitrogen-reducing (NIR) vesicles in actinorhizal plants, aid in nitrogen fixation, and facilitate early colonization of plants during primary succession. • Inhibit higher plants and cause diseases such as potato scab and responsible for ratoon stunting disease in sugarcane. Infect xylem and responsible for plant wilting in alfalfa, corn, tomato, and potato. Cause leafy gall syndrome in dicotyledonous, herbaceous plants.	• *Frankia* • *Streptomyces scabies* • *Leifsonia xyli*. • *Clavibacter michiganensis*. • *Rhodococcus fascians*.	[2, 10]
Endosymbiotic	• Produce bioactive compounds or plant growth regulators (PGRs) and protect crops from fungal infection. • Associate with marine sponges and serve as a promising source of novel antibiotic leads.	• *Streptomyces griseoviridis*. • *Arthrobacter*, *Brachybacterium*, *Brevibacterium*, *Corynebacterium*, *Dietzia*, *Microbacterium*, *Micrococcus*, *Micromonospora*, *Mycobacterium*, *Nocardiopsis*, *Rhodococcus*, *Rubrobacter*, *Salinispora*, and *Streptomyces*.	[2, 11, 12]
Gut	• Detoxify certain compounds, supply nutrients and vitamins, enhance growth performance, digest complex food sources, and provide protection against pathogenic	• *Rhodococcus rhodnii*, *Coriobacteriaceae*, *Bifidobacterium*, *Streptomyces*, and *Micromonospora*.	[2, 10]

Table 1.
Types of Actinobacteria and their relevant functions.

3. Applications of Actinobacteria

3.1 Applications of Actinobacteria in agriculture

Overuse of agrochemicals has led to significant deterioration in soil fertility and threatens to deprive a major population of essential food sources. This necessitates the need to implement natural methods for sustaining as well as developing our precious agricultural areas. Actinobacteria, a naturally occurring microorganism in the bulk soil or rhizospheric soil has caught the attention of almost all the researchers. Due to their extraordinary properties compared to other microbes, they are beneficial for improving the soil quality, enhancing plant growth, and thereby contributing toward the “Green Revolution” [2].

3.1.1 Actinobacteria as plant growth-promoting Rhizobacteria (PGPR)

Actinobacteria are ubiquitously present in soil with an average count of 5×10^{10}–6×10^{10} CFU/gm of soil [13]. They are usually found as dormant spores and develop into mycelial forms only in favorable environmental conditions [13]. As the soil depth increases, their population expands but only up to horizon C (regolith) [14]. Some of the important genera of Actinobacteria found in soil are *Streptomyces*, *Nocardia*, *Micromonospora*, *Actinoplanes*, and *Streptosporangium*, wherein *Streptomyces* alone can contribute to nearly 70% of the population [2]. Actinobacteria like other plant growth-promoting rhizobacteria (PGPR) can enhance plant growth either directly or indirectly (**Figure 1**) [14].

3.1.1.1 Role as biofertilizer

The three essential nutrients required by the plants for their proper growth are nitrogen, phosphorus, and potassium (NPK). These requirements are fulfilled by different soil microbes—Actinobacteria being the chief contender. NPK is required by plants for the synthesis of several macromolecules, biosynthesis of ATP, photosynthesis, and other cellular processes.

3.1.1.1.1 Nitrogen fixation

Nitrogen is a highly inert gas and has to be converted into readily bioavailable forms like ammonia, nitrates, or nitrites. This is attained through the process known as nitrogen fixation. Actinobacteria have been recognized to fix atmospheric nitrogen either symbiotically or under free-living conditions (**Table 2**). Two important genes required for this process are *nif* and *nod* genes. The *nif* gene encodes nitrogenase enzyme which is required for nitrogen-fixing (N-fixing) and the *nod* gene encodes Nod factors which are responsible for nodule formation [16]. Chemoattractant signals elicited by hosts lead to sequential events – attachment of bacteria to the root hair of host plants, curling of root hair, formation of infection thread, and bacterial establishment into the nodules [17].

Some endophytic Actinobacteria like *Arthrobacter*, *Agromyces* sp. ORS 1437, *Microbacterium FS-01, Mycobacteria*, and *Propionibacteria* can also fix nitrogen [14, 18]. With the advancement of molecular studies, several nifH-containing Actinobacteria (other than *Frankia* sp) as well as non-*Frankia* Actinomycetes like *Gordonibacter pamelaecae, Rothia mucilaginos*a, and *Slackia exigua* have been discovered leaving behind questions about diazotrophic origin and emergence

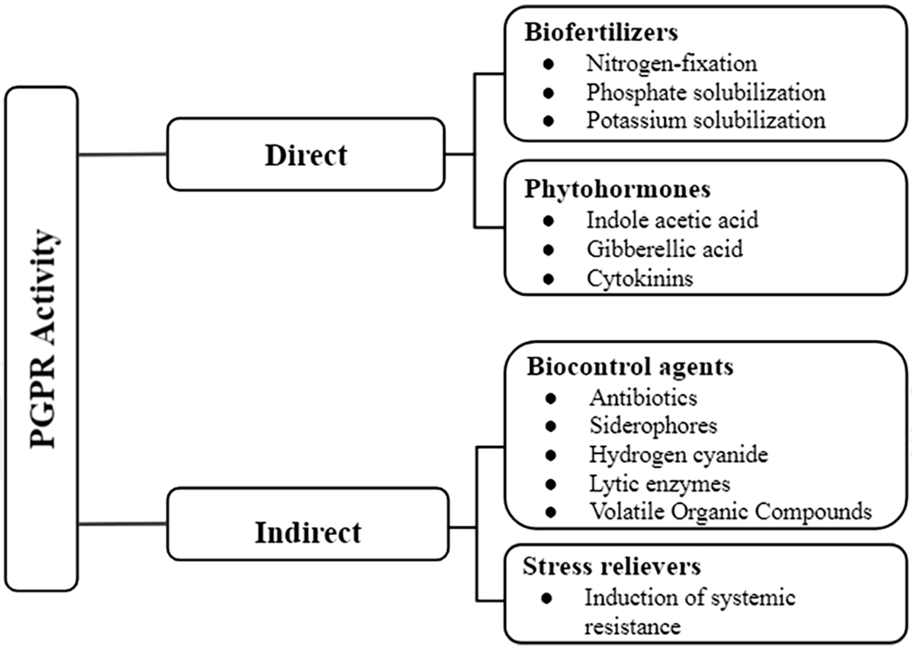

Figure 1.
Flow chart representing PGPR activity of Actinobacteria through direct and indirect methods.

N-fixing Actinobacteria	Association with plants	References
Corynebacterium sp. AN1	Promotes the growth of maize crop by relegating the level of acetylene.	[1]
Pseudonocardia dioxanivorans CB1190	Fixes dinitrogen symbionts. The only source of carbon and energy is 1,4-dioxane.	[1]
Streptomyces sp.	Provides nitrogen source as well as protects the leguminous plants like pea from pathogens.	[1, 15]
Frankia	Fixes nitrogen either under free-living conditions or symbiotically via actinonodules in higher non-leguminous plants like *Alnus*, *Casuarina*, and *Hippophae*.	[1, 14]
Micromonospora	Fixes nitrogen symbiotically via actinonodules in trees and shrubs.	[1]

Table 2.
N-fixing Actinobacteria and associated plants.

among Actinobacteria [1, 15]. Apart from this, Actinobacteria also forms symbiotic association with mycorrhiza by promoting hyphal elongation of symbiotic fungi. An example of such a symbiosis is found on the roots of sorghum and clover associated with *Streptomyces coelicolor* and *Streptomyces* sp. MCR9 and MCR24, respectively [14].

3.1.1.1.2 Phosphate solubilization

Phosphorus (P) is generally present in the soil in insoluble form and hence cannot be taken up by the plants for their nourishment. Not all the P provided by agrochemicals are utilized by plants. Unused soluble forms of P are fixed in the process with the aid of large quantities of cations (Zn^{2+}, Ca^{2+}, Al^{3+}, and Fe^{3+}). This in turn may result in eutrophication and depleted soil fertility [19]. Phosphorus-solubilizing microbes like Actinobacteria is an eco-friendly substitute to this, since they provide soluble P constantly due to their steady degrading activities. Two known mechanisms used by them are as follows:i) they secrete extracellular enzyme phytases which degrade phytate and ii) they create acidic environment near the rhizosphere by releasing various acids such as citric, gluconic, malic, oxalic, propionic, and succinic acids which solubilize the insoluble forms. Characteristic examples include *Arthrobacter*, *Gordonia*, *Kitasatospora*, *Kocuria kristinae* IARI-HHS2–64, *Micrococcus*, *Micromonospora* sp., *Micromonospora aurantiaca*, *Micromonospora endolithica*, *Rhodococcus*, *Streptomyces* sp., *Streptomyces griseus*, and *Thermobifida* [14, 15, 18, 20].

3.1.1.1.3 Potassium solubilization

Just like phosphorus, potassium (K) is also present in insoluble form in the soil and can be solubilized with the help of potassium-solubilizing microbes like Actinobacteria. The mechanisms implemented by them areas follows: (i) exchange and complexation reaction; (ii) production of organic acid which is subsequently followed by acidolysis; and (iii) chelation. Characteristic examples include *Arthrobacter* sp., *Microbacterium* FS-01, *Streptomyces* sp. KNC-2, and *Streptomyces* sp. TNC-1 [15, 18].

3.1.1.2 Production of phytohormones

Phytohormones like auxins (indole-acetic acid, IAA), gibberellins (GA3), and cytokinins are responsible for increasing the branching of root hair and widening the surface area, allowing the plants to take up more nutrients for their growth. Several Actinobacteria are responsible for the production of such phytohormones which have been listed in **Table 3**.

3.1.1.3 Role as biocontrol agents (BCAs)

Biological control simply means suppression of plant pathogens by other living organisms and controlling a variety of diseases. The microbial biocontrol agents (MBCAs) are target-specific with minimal impact on the rest of the plant population. They can sustain their effect for a longer duration and promote plant growth in an eco-friendly manner. MBCAs like Actinobacteria produce multifarious substances such as antibiotics, siderophores, hydrolytic enzymes, hydrogen cyanide (HCN), and other volatile organic compounds (VOCs) and guard the plants from the attacking phytopathogens via antagonistic effect [2, 22, 23].

3.1.1.3.1 Production of antibiotics

Streptothricin became the first antibiotic obtained from *Streptomyces* in the year 1942, and in 1944, Streptomycin was discovered. Since then, this microbe has been exploited for the discovery of many novel antibiotics [20]. Today *Streptomyces* alone contribute to two-third of the world's antibiotic production due to its extra-large DNA complement [2]. Antibiosis is enabled by the production of several groups of antibiotics ranging from aminoglycosides (streptomycin and kanamycin), ansamycins (rifampin), anthracyclines (doxorubicin), β-lactams (cephalosporins), macrolides (erythromycin and oleandomycin), and polyene (nystatin and levorin) to tetracycline [2, 15]. Some of them have been listed in **Table 4**.

Some Actinobacteria can produce a combination of antibiotics. For example, *Streptomyces violaceusniger* YCED9 produces three antifungal compounds—nigrecine, geldanamycin, and guanidyl fingine to keep a stringent

Actinobacteria	Phytohormones	Role
Nocardiopsis, *Streptomyces atrovirens*, *S. olivaceoviridis*, *S. rimosus*, *S. rochei*, and *S. viridis*.	IAA	Enhances the germination of seed, elongation of root as well as growth.
S. atroolivaceus	IAA	Promotes cell differentiation, hyphal elongation, and sporulation.
S. purpurascens NBRC 13077	IAA (low level)	Regulates the expression of biosynthetic gene, rhodomycin.
S. hygroscopicus TP_A045	Pteridic acids A and B (metabolites that exhibit auxin- like activity)	Promotes root elongation in common beans.
Actinomyces sp., *Arthrobacter*, *Micrococcus*, *Nocardia* sp., and *Streptomyces* sp.	GA3	Extends the tissues of stem leading to alteration in plant morphology and raises the height of the plant, overall biomass, and grain in common beans.
Arthrobacter, *Frankia* sp., *Leifsonia soli*, *Rhodococcus fascians*, and *S. turgidiscabies*	Cytokinins	Promotes cell division and enlargement and transfers signals from roots to shoots under environmental stresses, for example, in soybean.

Table 3.
Actinobacteria-producing phytohormones [14, 21].

check on the attacking pathogen [1]. Other antibiotic producers belonging to Actinobacteria are *Actinoplanes* (purpuromycins), *Microbispora* (microbiaeratin), *Micromonospora* (clostomicins), *Nocardia* (nocathiacins), and *Nocardiopsis* (thiopeptide antibiotic) [21].

3.1.1.3.2 Production of siderophores

Iron (Fe) is present in their insoluble forms, hydroxides, and oxyhydroxides in the soil which is unavailable to both the plants and the microbes. In order to cope with Fe deficiency, microbes started producing small-molecular-weight compounds called siderophores which are a specific carrier of ferric ions (Fe^{3+}). In addition to fulfilling the nutrient requirement for plant growth, the siderophores also act as BCA. They sequester (chelate) iron, form complexes with iron in a 1:1 ratio, create a competitive surrounding for pathogenic microorganisms, and remove the low-affinity siderophores of the pathogens. The process involves conversion of Fe^{3+} ions (insoluble form) to ferrous (Fe^{2+}) ions (soluble form) with the assistance of esterase enzymes. The Fe^{2+} ions are then released into the cells with the help of ATPase activity/proton motive force (PMF). For instance, *Streptomyces* protect against *Fusarium oxysporum* f. sp. *ciceri* under wilt sick field conditions on chickpea [14, 21]. *Streptomyces* sp. CMU.MH021 produces hydroxamate siderophores as well as IAA and slows down the hatching rate of eggs of nematode pathogens like *Meloidogyne incognita* [15]. Heterobactin siderophore of *Rhodococcus* and *Nocardia;* coelichelin and coelibactin peptide siderophores of *Streptomyces coelicolor*; enterobactin of *Streptomyces tendae*; oxachelin of *Streptomyces* sp. GW9/1258; erythrobactin, a hydroxamate-type siderophore of *Saccharopolyspora erythraea* SGT2; nocardamine, a cyclic siderophore of *Citricoccus* sp. KMM3890; desferrioxamine (DFO) B and E of *Salinispora*; tsukubachelin, a siderophore of *Streptomyces* sp. TM-34; foroxymithine of *Streptomyces* sp.; and amychelin, an uncommon mixed-ligand siderophore of *Amycolatopsis* sp. AA4 that modifies the developmental processes of *Streptomycetes*

Antibiotics	Actinobacteria	Role	References
Antibacterial and antifungal elements	*Streptomyces* sp.	Inhibits the growth of *Rhizoctonia solani*, a fungal pathogen of tomato.	[15]
Antifungal metabolite polyoxin B	*S. cacaoi* var. *asoensis*	Inhibits fungal pathogens in fruit, vegetables, and ornamental plants by interfering with fungal cell wall formation and inhibition of chitin synthase enzyme.	[20]
Antifungal metabolite polyoxin D	*S. cacaoi* var. *asoensis*	Inhibits rice sheath blight caused by *R. solani*.	[20]
Avermectins (a class of macrocyclic lactones)	*S. avermitilis*	Protects the host plant from nematode pathogens like *Meloidogyne incognita* and *Caenorhabditis elegans*.	[15]
Germicidin and hypnosin	*S. alboniger*	Inhibits spore germination.	[21]
Geldanamycin and elixophyllin	*S. hygroscopicus*	Suppresses *Rhizoctonia* root rot of pea.	[21]
Kasugamycin	*S. kasugaensis*	Exhibits antagonistic effect against fungal pathogen *Magnaporthe oryzae* and inhibits rice blast.	[24]
Mildiomycin	*Streptoverticillium rimofaciens*	Inhibits powdery mildews on various crops.	[5]
Naphthoquinone	*Streptomyces* sp.	Protects the host plant *Alnus glutinosa* from many bacterial and fungal pathogens.	[15]
Polyketides	*Streptomyces* sp. AP-123	Exhibits toxic effects on *Helicoverpa armigera* and *Spodoptera litura* larvae.	[20]
Polyene-like compounds related to guanidyl-containing macrocyclic lactones	*Streptomyces* sp.	Exhibits anti-*Fusarium* activity (AFA) against *Fusarium oxysporum*.	[21]
Streptomycin	*Streptomyces* sp.	Inhibits fire blight of pear caused by *Erwinia amylovora* (a pome fruit pathogen).	[25]

Table 4.
Antibiotic-producing Streptomyces along with their inhibitory role.

surrounding them are some of the few examples of siderophores produced by Actinobacteria [14, 21, 26].

3.1.1.3.3 Production of hydrogen cyanide (HCN)

Hydrogen cyanide (HCN) acts as another BCA and inhibits the phytopathogens by hampering the respiratory electron transport chain system. Moreover, the production of HCN also boosts up other mineral solubilization like phosphorus, improving the quality of the soil and hence crop production. *Arthrobacter* and *Streptomyces* are capable of producing HCN. *Streptomyces* sp. from roots of *Solanum nigrum* inhibit fungal disease—root rot and damping-off of tomato caused by *Fusarium oxysporum* f. sp. *radicis lycopersici* [15, 27].

3.1.1.3.4 Production of lytic enzymes

The cell walls of most of the phytopathogens are composed of chitin, glucan, cellulose, hemicellulose, lignins, pectins, proteins, keratins, xylans, dextrans, and lipids. The soil microbes can target the cell wall through the specific enzymes produced by them and thus inhibit the growth of these pathogens. Several enzymes produced by Actinobacteria are amylases, cellulases, chitinases, dextranases, glucanases, hemicellulases, keratinases, ligninases, lipases, nucleases, pectinases, peptidases, peroxidases, proteinases, and xylanases [14]. Some of them have been listed in **Table 5**.

The extracellular enzymes show an enhanced effect when used synergistically with the antibiotics. For example, antibiotics along with enzyme chitinase produced by *S. lydicus* WYEC108 works synergistically against pathogen *Pythium ultimum* which is responsible for causing fungal root and seed diseases [20].

3.1.1.3.5 Production of volatile organic compounds (VOCs)

Actinomycetes are known to produce geosmin. These volatile organic compounds result in the characteristic odor of the soil and at times also translate into an earthly taste of potable water. Besides imparting odor and taste, these actinomycetes-derived VOCs are also known to have biocontrol attributes [5]. The very ability to diffuse comfortably through soil particles and damage pathogens makes it a potent and sustainable alternative for agrochemicals. For instance, germination of *Botrytis cinerea* and *Penicillium chrysogenum* spores are inhibited by *Streptomyces coelicolor*. Moreover, VOCs from *S. globisporus* and *S. philanthi* have shown activity against *Botrytis cinerea* and *Fusarium moniliforme*, respectively. Pathogen-causing downy blight in litchi—*Peronophythora litchii*, can also be actively targeted by VOCs from *S. fimicarius* [15]. Another VOC, methyl vinyl ketone from *S. griseoruber* has been reported to inhibit *Cladosporium cladosporioides* spore germination [20].

3.1.1.4 Role as stress reliever

It is the genetic makeup of the plant which decides the productivity and their ability to adapt resistance against various abiotic stresses and phytopathogens [15]. Plants have adapted certain mechanisms like the induced systemic resistance (ISR) and systemic acquired resistance (SAR). Upon arrival of stressful conditions, plants start synthesizing elevated levels of stress-responsive hormone—ethylene (ET) that causes premature death of plants. 1-aminocyclopropane-1-carboxylate (ACC) is the precursor of ethylene hormone. Actinobacteria have the capability to survive in different types of biotic and abiotic stress factors, such as drought, extreme temperatures, floods, and salinity, but the plants might get affected, resulting in the low production of crops [14]. To enhance the plant growth, tolerant strains like Actinobacteria are inoculated. *Amycolatopsis*, *Mycobacterium*, *Nocardia*, *Rhodococcus*, and *Streptomyces* produce a specific enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase to target ACC and convert it into ammonia and α-ketobutyrate. Some of the strategies adopted by *Streptomyces padanus* for drought tolerance involve accumulation of callose, cell wall lignification, and stimulation of high levels of osmotic pressure of plant cells [14].

For instance, under the onset of saline conditions, *Streptomyces* sp. enhances the growth of maize and wheat. It has been found that under *in vitro* conditions of high concentration of NaCl, *Arabidopsis* seedlings showed enhanced growth of biomass and lateral roots when inoculated with *Streptomyces* sp. [14]. It has also

Enzymes	Actinobacteria	Comments	References
L-asparaginase	*Nocardia* sp, *Streptomyces karnatakensis*, *S. albidoflavus*, and *S. griseus*	—	[2]
β-1,3; β-1,4; and β-1,6glucanases	*Actinoplanes philippinensis*, *A. campanulatus*, *Microbispora rosea*, *Micromonospora chalcea*, *Streptomyces griseoloalbus,* and S. spiralis.	Inhibit *Pythium aphanidermatum* and *Phytophthora fragariae*, causal agent of damping-off disease in seedlings of cucumber (*Cucumis sativus* L.) and raspberry.	[15, 20]
Proteases	*Streptomyces* sp. strain A6	Manages anthracnose on tomato fruits and inhibits diseases associated with *Fusarium udum*.	[20]
Keratinase	*Nocardiopsis* sp. SD5	Degrades the poultry chicken feather.	[2]
Chitinase and glucanase	*S. cavourensis* SY224	Manages anthracnose in pepper.	[20]
Chitinase	*S. plymuthica* C48 *S. violaceusniger* XL-2	• Inhibits spore germination of *Botrytis cinerea*. • Suppresses wood-rotting fungi.	[20]
Chitinases, glucanases, cellulases, lipases, and proteases	*Streptomyces* sp. 9P	• Inhibits *Alternaria brassicae* infecting plants of *Brassica* species. • Inhibits C*olletotrichum gloeosporioides*, infecting perennial plants. • Inhibits *Rhizoctonia solani*, a phytopathogen with a wide host range. • Inhibits *Phytophthora capsici*, infecting commercial crops like peppers.	[15]

Table 5.
Lytic enzymes produced by Actinobacteria and their inhibitory effect.

been revealed that *Streptomyces* sp. produces the enzyme ACC deaminase which in turn resulted in an increase in the level of calcium and potassium and allows the plant *Oryza sativa* to survive under the saline conditions. In addition, siderophore production and other PGP traits enable them to resist heavy metal toxicity [15]. *S. coelicolor* and *S. olivaceus* are examples of drought-tolerant species and have a tremendous plant growth-enhancing capacity. *Citricoccus zhacaiensis* promotes germination rate and plant growth as well as produces different enzymes and hormones like phosphate-solubilizing enzymes, ACC deaminase, IAA, and GA3 to cope up with the high osmotic pressure conditions [15].

3.2 Applications of Actinobacteria in nanotechnology

Nanotechnology research is among the most rapidly developing scientific and technological fields [28]. It is a transdisciplinary field which has an impact in the domains of agriculture, medicine, and industry [29]. Nanotechnology allows us to produce nanoparticles with specific properties for use in a wide range of applications [30]. Integration of nanotechnology with biotechnology has evolved as a new biosynthetic and environment-friendly approach for the production of nanomaterials [31]. Nanoparticles have received a lot of attention recently because of their unique qualities, and they are being employed in a lot of different fields like pharmaceuticals, nanoengineering, drug delivery, nanoantibiotics, catalysis, electronics, sensor creation, and other areas [30, 32]. There are two techniques which are used for the synthesis of nanoparticles: (1) the top-down technique, which involves breaking down bulk materials into nanosized materials and (2) the bottom-up technique, which involves assembling the atoms and molecules into molecular structures in the nanoscale range [33, 34]. The top-down technique is quite expensive, and it also produces exceedingly poisonous substances as by-products and consumes a lot of energy. As a result, a biological, ecological-friendly strategy for pollution-free, nontoxic, biodegradable synthesis of technologically relevant nanomaterials becomes critical [34].

3.2.1 Biological synthesis of nanoparticles by Actinobacteria

Synthesis of nanoparticles using a biological system is a rapid, efficient, economical, nontoxic, and environmental-friendly method. Many researchers have investigated the production of desired nanoparticles using Actinobacteria, bacteria, microalgae, yeast, viruses, and fungi [30, 35]. The use of microorganisms, enzymes, and plant extracts to produce nanoparticles has also been proposed as a feasible biological technique [36]. Microorganisms such as Actinobacteria are capable of producing nanoparticles which are widely used as novel therapeutics such as antimicrobial, anticancer agents, anti-biofouling agents, antifungals, and antiparasitic (**Figure 2**) [37]. Inorganic compounds are produced by Actinobacteria either intracellularly or extracellularly, and they are often nanoscale in size and morphology. Most harmful heavy metals are resistant to Actinobacteria due to chemical detoxification as well as energy-dependent ion efflux from the cell through membrane proteins that operate as ATPase, chemiosmotic cation, or proton anti-transporters [38, 39]. The main principle behind the synthesis of nanoparticles is that actinobacterial enzymes reduce metal ions to stable nanoparticles when provided with metal ions as substrates. For example, the synthesis of silver nanoparticles (AgNPs) usually uses silver nitrate solution ($AgNO_3$) as a substrate for the secreting enzymes, and the substrates used for the production of gold nanoparticles (AuNPs) are chloroauric acid solutions ($AuCl_4$). Nanoparticles can also be produced with other metals like zinc, copper, and manganese [34]. Actinobacterial detoxification can occur via extracellular biosorption, precipitation biomineralization, or complexation, or through intracellular bioaccumulation [28]. Studies of the *Arthrobacter* and *Streptomyces* genera as potential nanofactories have been conducted in an effort to discover safe and clean techniques for synthesizing gold and silver nanoparticles [2]. There was a wide variety of silver nanoparticle synthesizing Actinobacteria, found in the marine environment, with 25 isolates out of 49 generating silver nanoparticles. The genera of bacteria synthesizing silver nanoparticles are *Actinopolyspora* sp., *Kibdelosporangium* sp., *Nocardiopsis* sp., *Saccharopolyspora* sp., *Streptomyces* sp., *Thermoactinomyces* sp., and *Thermomonospora* sp. [2].

3.2.1.1 Intracellular synthesis of actinobacterial nanoparticles

Additional processing procedures, such as ultrasonic treatment or interaction with appropriate detergents, are necessary to liberate the intracellularly produced nanoparticles. This can be used to recover valuable metals from mine wastes and metal leachates. Metal nanoparticles that have been biomatrixed could be employed as catalysts in a variety of chemical processes [28, 40]. Gold nanoparticles

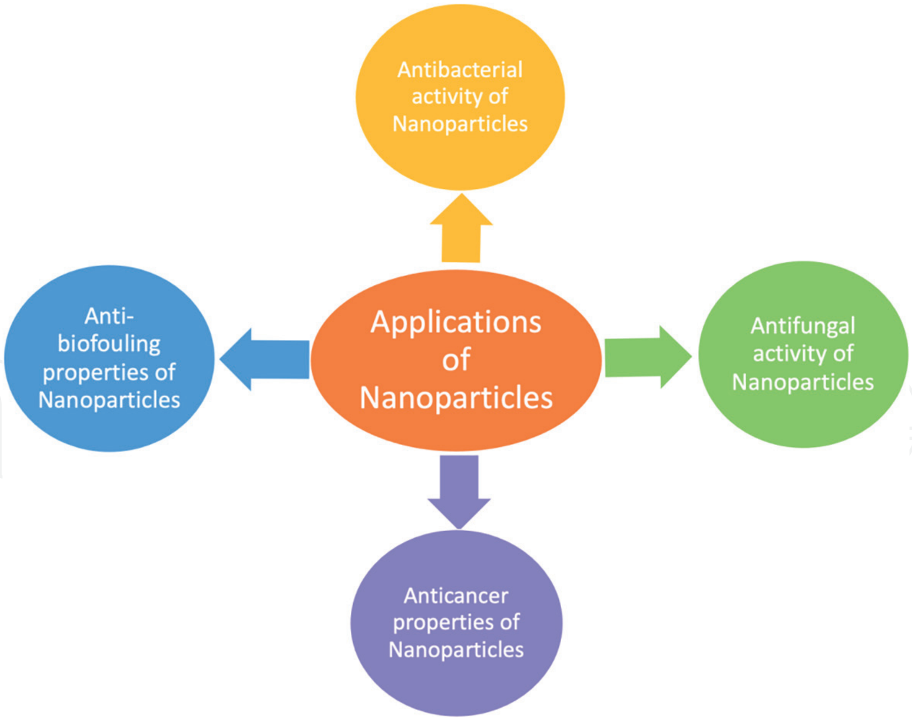

Figure 2.
Applications of biologically synthesized nanoparticle.

synthesized by alkalotolerant *Actinomycetes*, *Rhodococcus* sp., were characterized for the first time by Ahmad et al. [41]. The reduction of zinc sulfate ($ZnSO_4$) and manganese sulfate ($MnSO_4$) using *Streptomyces* sp. HBUM171191 proved to be a suitable intracellular method of producing zinc and manganese nanoparticles (10–20 nm) [34]. The intracellular synthesis of silver nanoparticles (AgNPs) from *Aspergillus fumigatus* and *Streptomyces* sp. was compared by Alani et al. The change in color from colorless to a light brownish to dark brownish was used by them to identify nanoparticle production [42]. *Streptomyces* sp. (strains: D10, ANS2, HM10 and MSU) isolated from the Himalayan Mountain ranges were capable of producing spherical and rod-shaped intracellular gold nanoparticles (AuNPs) while also exhibiting antibacterial activity [43].

3.2.1.2 Extracellular synthesis of actinobacterial nanoparticles

The ability of Actinobacteria to synthesize extracellular metal nanoparticles is dependent on the location of reductive elements within the cell. It entails the use of soluble secretory enzymes or cell wall reductive enzymes that can recognize metal ions and reduce them to nanoparticles [44]. A study focused on different actinobacterial strains for gold and AgNP production with diverse morphologies and size distributions. They discovered that when an alkali thermophilic *Thermomonospora* sp. is exposed to gold chloride, it produces spherical AuNPs with a limited size distribution with a diameter of 8 nm [45]. Extracellular AgNPs with a diameter of 68.33 nm were generated by a soil isolate, *Streptomyces* sp. JAR, and showed antibacterial efficacy against a wide range of fungal and bacterial diseases [46]. The anti-dermatophytic characteristics of biologically synthesized, cubical shaped AuNPs (90 nm size) obtained from the culture extract of *Streptomyces* sp. VITDDK3 were documented, as well as their antifungal activities against *Microphyton gypseum* and *Trichophyton rubrum* [47]. Other extracellular producers of AgNPs have been identified as *Rhodococcus* sp., a metabolically flexible Actinobacteria, and *Streptomyces glaucus* 71MD, a novel actinobacterial strain [48, 49].

3.2.2 Antibacterial activity of nanoparticles

Nanoparticles produced using a variety of technologies have been applied in a variety of *in vitro* diagnostic procedures [50, 51]. The antibacterial activity of gold and silver nanoparticles against human and animal diseases has been widely reported [28, 43, 47]. For achieving synergistic effects with biomolecules, the antibacterial mechanism of developed nanoparticles is crucial. Actinobacteria, primarily the species *Streptomyces* and *Micromonospora*, are known to be the source of about 80% of the world's antibiotics [2]. *Streptomyces* are the primary producers of antibiotics in the pharmaceutical industry since they produce around 7600 compounds, many of which are secondary metabolic products that are potent antibiotics [52, 53].

The production of reactive oxygen species (ROS) by metal nanoparticles is the most common mechanism of cellular toxicity [54]. Gold and silver nanoparticles have antibacterial capabilities due to their slow oxidation and release of Ag^+ and Au^{3+} ions into the environment, making them suitable biocidal agents [34]. Nanoparticles having a large surface area possess high antibacterial capabilities, allowing them to make the most contact with the environment possible [55]. By disrupting cellular permeability and respiration, metal nanoparticles have proved to have good antibacterial capabilities. The positively charged metal ions breach the bacterial cell wall by adhering to and breaking the negatively charged bacterial cell wall, causing protein denaturation, DNA replication interference, and eventually the organism's death [56, 57]. Silver nanoparticles induce cell death by breaking the plasma membrane or inhibiting respiration by converting the cell wall oxygen and sulfhydryl (–SH) groups to RS-SR groups [58, 59]. *Streptomyces viridogens*-derived gold nanoparticles (AuNPs) exhibited remarkable antibacterial efficacy against *Staphylococcus aureus* and *Escherichia coli* [43]. The potential antibacterial impact of silver nanoparticles synthesized from *Streptomyces albidoflavus* using an environmentally benign approach was revealed against several gram-positive and gram-negative species. *Streptomyces* sp. [60]. AgNPs were found to be active against the anti-extensive spectrum beta-lactamase-producing strain Klebsiella pneumoniae (ATCC 700603), as well as other therapeutically relevant pathogens like *E. coli* and *Citrobacter* species [34]. Silver nanoparticles (AgNPs) from a new *Streptomyces* sp. BDUKAS10 strain also showed improved bactericidal action against some bacteria [61]. Some food microbe pathogens, such as *Bacillus cereus*, *E. coli*, and *S. aureus*, were eliminated using AgNPs from *Streptomyces albogriseolus* [34, 62].

3.2.3 Antifungal activity of nanoparticles

In recent years, fungal infections have become increasingly widespread, and silver nanoparticles have evolved as prospective antifungal medicines. Due to cancer chemotherapy or human immunodeficiency virus infections, fungal infections are more typically encountered in immune-deficient patients [28, 63]. Gold nanoparticles (AuNPs) produced utilizing a sustainable technique with *Streptomyces* sp. VITDDK3 have good antifungal action against *Microsporum gypseum* and *Trichophyton rubrum* by causing membrane potential to fluctuate and by inhibiting the ATP synthase activity, which causes a general decline in the metabolic activities. The vulnerability of the pathogen's cell wall and the toxicity of metallic gold could explain the antidermatophytic activity of the produced AuNPs [47]. *Fusarium* sp. and *Aspergillus terreus* JAS1 were suppressed by biologically produced silver nanoparticles made with *Streptomyces* sp. JAR1 [46]. Silver nanoparticles produced from *Streptomyces* sp. VITBT7 showed inhibitory action against *Aspergillus niger* and *Aspergillus fumigatus* (MTCC 3002), whereas silver nanoparticles produced from *Streptomyces* sp. VITPK1 demonstrated promising antifungal activity against *Candida krusei*, *Candida tropicalis*, and *Candida albicans* [30, 64].

3.2.4 Anticancer properties of nanoparticles

Cancer is one of the most common causes of death, accounting for one out of every six fatalities in 2018. However, 70% of cancer deaths occur in middle- and low-income nations [65]. The most frequent cancer treatment and management methods include surgery, chemotherapy, hormone therapy, and radiation therapy. However, in recent times, nanotechnology-based therapeutic and diagnostic techniques have demonstrated potential for improving cancer treatment [66]. The production of nanoparticles was reported by utilizing a novel Nocardiopsis sp. MBRC-1 isolated from marine sediment samples off the coast of Busan, South Korea [67]. In vitro cytotoxicity of the biosynthesized AgNPs against the human cervical cancer cell line (HeLa) was observed, along with high antimicrobial activity against bacteria and fungi [67]. Silver nanoparticles synthesized with *S. naganishii* (MA7) from the Salem area of Tamil Nadu, India, were also found to have cytotoxic properties against HeLa cancer cell lines [68].

3.2.5 Anti-biofouling properties of nanoparticles

Anti-biofouling is a method of removing biofouling, which occurs when bacteria cluster on wetted surfaces, forming biofilms and emitting a foul odor. In industries such as medicine, treatment plants, sensor sensitivity, and transportation, biofilms cause operational issues. Biofilm accumulations can be efficiently prevented or eliminated by utilizing the anti-biofouling characteristics of biosynthesized nanoparticles [69]. According to Shanmugasundaram et al., *Streptomyces naganishii* MA7 biosynthesized spherical, 5–50-nm-sized silver nanoparticles that were efficient against 10 different biofouling microorganisms *in vitro* [34, 68].

3.3 Application of Actinobacteria in bioremediation

Heavy metals are natural components of soil, and they work as cofactors in a variety of enzymes. Heavy metal pollution of the biosphere has increased as a result of industrial evolution, which often becomes hazardous at high concentrations. The discharge of heavy metals from the electroplating industry is one of the most significant sources of heavy metal toxicity around the globe [70]. Heavy metals such as copper, mercury, chromium, lead, zinc, and cadmium are commonly found in the effluents/wastewater generated by the industry. Continuous exposure to heavy metals has been linked to infant growth retardation, the onset of numerous cancers, and liver and kidney damage. Bioremediation is an efficient and sustainable process of reverting a contaminated environment to its original state using microbes or their enzymes [71]. In soils, *Actinomycetes* comprise a significant microbial population, and they are also extensively distributed in nature [72]. Heavy metal tolerance, as well as metabolic diversity and unique growth properties of *Actinomycetes*, such as mycelium development and relatively quick colonization of selected substrates, vindicate their capabilities as excellent bioremediation agents [73].

3.3.1 Bioremediation of toxic heavy metals

3.3.1.1 Copper bioremediation

Copper (Cu) is a vital heavy metal with numerous functions in biological systems, such as cellular respiration, pigment formation, connective tissue growth, and neurotransmitter generation [74]. Copper becomes hazardous at high concentrations [75], causing behavioral and mental problems, renal damage, sickle cell anemia, dermatitis, schizophrenia, and nervous system disorders like Parkinson's and Alzheimer's [76]. Copper has been widely distributed in soil, silt, trash, and wastewater as a result of industrial use and discharge, posing significant environmental concerns. *Streptomyces* AB5A [77], *Amycolatopsis* [78], and *Kineococcus radiotolerans* [79] are some of the Actinobacteria involved in copper bioremediation. Extracellular cupric reductase activity was found in *Streptomyces* sp. AB2A. In both copper-adapted and non-adapted cells, *Amycolatopsis tucumanensis* DSM 45259 displayed effective cupric reductase activity. The copper-specific biosorption capacity of *A. tucumanensis* DSM 45259 was validated by subcellular fractionation experiments, which revealed that the retained copper was connected with the extracellular fraction (exopolymer, 40%), but mostly within the cells [80]. *Streptomyces* sp. WW1 identified from the wastewater treatment plant in Saudi Arabia has been found to successfully remove copper.

3.3.1.2 Chromium bioremediation

Chromium is most commonly found as chromite ($FeCr_2O_4$) in nature. Cr (VI), an oxidized form of chromium, is potentially poisonous, induces allergic dermatitis, and has carcinogenic, mutagenic, and teratogenic effects on biological organisms [81]. Trivalent chromium is 100 times more hazardous and 1000 times more mutagenic than hexavalent chromium compounds [73]. Das and Chandra [82] were the first to document the reduction of Cr (VI) by *Streptomyces*, while Laxman and More [83] were the first to report the reduction of Cr (VI) by *Streptomyces griseus* [82, 83]. *Microbacterium*, *Arthrobacter*, and *Streptomyces* have all been found to reduce Cr (VI) [83, 84]. The reduction of Cr (VI) by *Streptomyces* sp. MC1 bioemulsifiers were utilized as a washing agent to improve soil-bound metal desorption [85]. When glycerol and urea were employed as sources of carbon and nitrogen, *A. tucumanensis* DSM 45259 generated an emulsifier. Under harsh conditions of pH, temperature, and salt content, the bioemulsifiers demonstrated remarkable levels of stability. For the remediation of hexavalent chromium compounds, microbial emulsifiers based on remediation technologies appear to be more promising. *Arthrobacter* and *Amycolatopsis* are two actinobacterial genera active in chromium bioremediation [86, 87]. Other species involved in chromium bioremediation are *Halomonas* sp. [88], *Flexivirga alba* [89], *Friedmanniella antarctica* [90], and *Intrasporangium chromatireducens* [91].

3.3.1.3 Mercury bioremediation

Mercury is a highly hazardous heavy metal that has been associated with kidney damage and cardiovascular problems. Mercury pollution is mostly caused by discharges from refineries and industries, as well as human activities such as the burning of coal and petroleum, the use of mercurial fungicides in agriculture, and the use of mercury as a catalyst in industry [92]. Mercury resistance has been demonstrated in two *Actinomycete* strains, CHR3 and CHR28, obtained from metal-contaminated areas in Baltimore's Inner Harbor, USA [93]. The biomass of *Streptomyces* VITSVK9 was employed for mercury biosorption, and it showed a high metal tolerance capacity [94]. TY046-017, a *Streptomyces* isolated from tin tailings, also demonstrated possible tolerance to mercury.

3.3.1.4 Lead bioremediation

Lead is a neurotoxic substance that can build up in both soft and hard tissues, causing neurological problems and affecting physical development. Corrosion of household plumbing, brass and bronze fittings, and lead-based solders are prominent sources of these contaminants [95]. Metal tolerance was shown in *Streptomyces* VITSVK9 biomass and *Streptomyces* sp. BN3 which was discovered in Moroccan mine waste [96]. The biosorption of heavy metal Pb (II) by *Streptomyces* VITSVK5 spp. biomass was concentration- and pH-dependent. Heavy metal tolerance and lead buildup were observed in *Streptomyces* isolated from abandoned Moroccan mines [94, 96].

3.3.1.5 Zinc bioremediation

The free zinc ion in solution is extremely harmful to bacteria, plants, invertebrates, and even vertebrate fish, although it is less dangerous to humans. In humans, zinc toxicity is caused by zinc overload and hazardous overexposure [70]. Three strains of *Streptomyces* NGP (JX843532), *Streptomyces albogriseolus* (JX843531), and *Streptomyces variabilis* (JX43530) were recovered from a coastal marine soil sample in Tamil Nadu, India, and showed high levels of zinc biosorption. Strain WW1 of *Streptomyces* sp. obtained from the wastewater treatment plant in Saudi Arabia exhibited biosorption of zinc.

3.3.2 Bioremediation of pesticides

Agricultural production is one of the greatest and also most important economic activities on earth; thus, protecting it against pest infestations is a must. Agricultural runoff contaminates aquatic habitats with numerous residues of pollutants such as insecticides. Pesticides and fertilizers pollute local water bodies, causing detrimental effects in humans through food and drinking water. Pesticide residues have been found in groundwater and drinking water in India and around the world, according to several researchers [71, 97]. Yadav et al. [98] published a comprehensive review that found long-lasting pesticides in multi-component settings. Pesticides such as dichlorodiphenyltrichloroethane (DDT), endosulfan, hexachlorocyclohexane (HCH), and parathion methyl were detected in freshwater bodies, and several of them were classified as persistent organic pollutants (POPs). Since soil provides varied binding sites for these hydrophobic contaminants, the preservation of HCH isomers in various soil types inhibits the breakdown process [98]. The solubility of pesticides in water, their adsorption by soil particles, and their persistence all play a role in their mobility in soil compartments. Since it provides a multitude of binding sites for organic contaminants, especially hydrophobic chemicals, organic matter concentration is a characteristic that defines pesticide retention in soil and sediments [99].

A class of synthetic organic compounds known as organochlorine pesticides (POs) is composed of chlorine-containing hydrocarbons that have had one or more hydrogen atoms exchanged for chlorine atoms. These compounds may also contain other elements like oxygen or sulfur. Due to their toxicity, prolonged persistence, low biodegradability, widespread availability in the environment, and long-term consequences on wildlife and humans, many insecticides have been phased out of usage. Furthermore, their physicochemical qualities combine to allow them to traverse great distances [71].

3.3.2.1 Harmful effects of pesticides on human health

Acute intoxication is caused by high dosage of organophosphorus (OP) insecticides. Gastrointestinal discomfort, perspiration, muscle spasms, muscle weakness, bronchospasm, high blood pressure, bradycardia, central nervous system depression, and coma are all indications of this type of poisoning. People who have been exposed to OP for a long time develop a pesticide-related sickness, which can include headaches, dizziness, abdominal discomfort, nausea, blurred vision, vomiting, and chest tightness [100]. Insecticides containing carbamates have been implicated with the development of respiratory illnesses. Organochlorine (OC)-based insecticides pose the most serious and dangerous harm. They are difficult to degrade because they are lipid-soluble and have a high rate of persistence. Infertility, genital malignancies, tumors of the reproductive organs, neurotoxicity, and immunotoxicity are among the harmful effects of these chemicals [101].

3.3.2.2 Degradation of pesticides by Actinobacteria

Potential candidates for the degradation of resistant inorganic and organic contaminants are Actinobacteria. The most common pesticide-degrading Actinobacteria are *Arthrobacter*, *Streptomyces*, *Janibacter*, *Kokuria*, *Rhodococcus*, *Mycobacterium*, *Nocardia*, *Frankia*, *Pseudonocardia*, and *Mycobacterium* (**Table 6**). These bacteria are capable of growing and degrading a variety of pesticide chemical families, including carbamate (CB), organophosphorus (OP), organochlorine (OC), ureas, pyrethroids, and chloroacetanilide, among others [71]. Since members of the *Arthrobacter* genus exhibit diverse catabolic pathways for the detoxification of these substances, the majority of which are plasmid-encoded, the genus has been recognized as a degrader of several xenobiotics. Because of their dietary flexibility and resistance to environmental stress, this genus of microorganisms is found all over the world. *Arthrobacter* sp. AK-YN10 has been found to use plasmid-encoded information to degrade atrazine to cyanuric acid [105]. Endosulfan, which is based on organochlorines, is detoxified to endosulfan sulfate, which is then eliminated metabolically [102]. Atrazine is an effective nitrogen and carbon source for *Rhodococcus* sp. BCH2 [106].

Streptomyces aureus HP-S 01 was found to detoxify deltamethrin to 2-hydroxy-4-methoxy benzophenone and several other pyrethroids [104]. *Streptomyces* sp. M-7 has been discovered to have multi-pesticide resistance and can detoxify a variety of organochlorine pesticides such as aldrin, DDT, chlordecone (CLD), heptachlor, and dieldrin [107]. In soil microcosm assays, it may remove up to 78% gamma-HCH. *Streptomyces* sp. AC1-6 and ISP-4 can remove diazinon by up to 90%. Immobilized cells have various advantages over free suspended cells, including increased microbe retention in the reactor, improved cellular viability, and cell toxicity prevention, among other things [108]. Microbial and enzyme immobilization-mediated bioremediation procedures are more efficient, with a higher biodegradation rate [109]. Four distinct matrices were used to immobilize *Streptomyces* strains, either as pure cultures or as part of a consortium (polyvinyl alcohol, cloth sachets, silicone tubes, and agar). Immobilized microorganisms removed considerably more lindane than free cells. Additionally, the cells might be reused twice more before being discarded, lowering the overall cost of the biotechnology process [110].

Microorganism	Pesticide	Isolation sample	References
Arthrobacter sp.	Organochlorines (α-endosulfan)	Soil from different agricultural fields, contaminated by pesticides, India	[102]
Arthrobacter sp. BS1, BS2 and SED1	Urea (diuron)	Soil from the interface between a vineyard and the Morcille river, France	[103]
Streptomyces aureus HP-S-01	Pyrethroid (deltamethrin)	Activated sludge samples from an aerobic pyrethroid-manufacturing wastewater	[104]

Table 6.
General characteristics of main genera of pesticide-degrading Actinobacteria.

3.3.3 Bioremediation of petroleum refinery effluent

Petroleum is a heterogenous mixture of hydrocarbons and resins which contains toluene, benzopyrene, benzene, and naphthalene. The majority of them are stable and poisonous and can cause cancer [111]. Bacteria and Actinobacteria (**Table 7**) are both excellent options for microbial oil recovery. Natural attenuation processes and biodegradation are being used to bioremediate petroleum-contaminated soil. For petroleum refinery effluent, bioaugmentation and compositing are effective remediation strategies [121]. However, because of the negative effects of the environment on microbial life, such as disintegration of cell membranes, denaturation of enzymes, poor solubility of oxygen, low solubility of hydrocarbons, and desiccation, employing Actinobacteria is limited [122]. *Pseudomonas* sp. and *Azotobacter vinelandii* are known to decompose petroleum. *Burkholderia cepacia* is capable of degrading hundreds of organic compounds. Microbial growth and activity are aided by the conversion of hydrocarbons into carbon dioxide and water, which releases energy [123]. Diesel was degraded by *Pseudomonas* sp., which removed long- and medium-chain alkanes [124]. In several treatment techniques devised by Wang et al., a microbial consortium consisting of *Actinomadura* sp., *Brevibacillus* sp., and an uncultured bacterial clone improved oil recovery for biopolymer manufacture [125].

By introducing bioemulsifiers and biosurfactants into the environment, the rate of bioremediation/biodegradation of organic contaminants improves [126]. It is dependent on the mechanism that is engaged in the interactions between microbial cells and insoluble hydrocarbons in surface-active compounds (SACs): (i) emulsification; (ii) micellarization; (iii) adhesion-deadhesion of microorganisms to and from hydrocarbons; and (iv) desorption of contaminants [126, 127]. The use of

Compounds	Microorganisms	References
Alkanes	*Acinetobacter calcoaceticus*	[112]
	Nocardia erythropolis	[113]
	Pseudomonas sp.	[114]
Mono-aromatic hydrocarbons	*Pseudomonas sp.*	[115]
	Sphingomonas paucimobilis	[116]
Poly-aromatic hydrocarbons	*Achromobacter sp., Mycobacterium sp., Pseudomonas sp., Mycobacterium flavescens, Rhodococcus sp.*	[115, 117–120]

Table 7.
Actinobacteria capable of degrading petroleum hydrocarbon.

surfactants aids in the solubility of petroleum components because diesel oil biosurfactants increase oil mobility and bioavailability, hence improving biodegradation rates [128]. As a possible biosurfactant producer, *Nocardiopsis* B4 was discovered; this strain is important in the breakdown of poly-aromatic hydrocarbons (PAHs) in soils. A wide range of temperature, pH, and salt concentrations did not affect the biosurfactant activity, demonstrating its suitability for bioremediation [129].

4. Conclusion

Actinobacteria through its unique capabilities have gained importance in the field of agriculture, pharmaceuticals, industry, nanotechnology, and many more. *Streptomyces* is the most common genera among them. They possess several PGP traits such as biofertilizers, phosphorus and potassium solubilization, production of siderophores, antibiotics, phytohormones, and biological nitrogen fixation. Furthermore, nanotechnology research being the most rapidly developing fields is using actinobacterial biosynthesis of nanoparticles which is both environment-friendly and cost-effective, and the nanoparticles which are produced as a result show potential biological properties such as antibacterial activities, antifungal activities, anticancer properties, anti-biofouling properties. The combination of synthesizing methodologies with biological processes has resulted in the development of nanoparticles which are used in a number of *in vitro* diagnostic methods. Apart from this, toxic heavy metals like chromium, zinc, lead, and copper and pesticides can be sustainably removed using this microbe. The degradation of pesticides whose accumulation otherwise causes biomagnification is possible with the help of this microbe. Actinobacterial genera have also proven versatile to bring about the degradation of xenobiotic pollutants in the nutrient starvation conditions in the soil and their capability of using these toxic compounds as their nutrient source, mainly a source of carbon is something that speeds up the process of degradation. Cocktail of microbes of this genus is effective in causing faster degradation. Hence, this microbe is quite adaptive for maintaining the environment eco-friendly.

Conflict of interest

None to declare.

List of abbreviations

ACC	1-aminocyclopropane-1-carboxylate
AFA	anti-*Fusarium* activity
BCAs	biocontrol agents
HCN	hydrogen cyanide
HeLa	human cervical cancer cell line
IAA	indole-acetic acid
ISR	induced systemic resistance
MBCAs	microbial biocontrol agents
PAHs	poly-aromatic hydrocarbons
PGPR	plant growth-promoting rhizobacteria
PGRs	plant growth regulators
ROS	reactive oxygen species
AuNP	gold nanoparticles

AgNP	silver nanoparticles
SACs	surface-active compounds
SAR	systemic acquired resistance
VOCs	volatile organic compounds

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