Microsphere (2025) 3(1): 269-289
https://doi.org/10.59118/CDPT2657

Review

Actinobacteria: Boon or Bane?

Aeshna Nigam[1#] · Simran Jit[2#] · Jaspreet Kaur[3] · Vaishnavi Rajagopalan[4] · Pranavi Kumar[5] · Mansi Verma[6*]

Received:24 August 2024 / Accepted: 06 December 2024 / Published online: 30 September 2025

Abstract

For centuries, Actinobacteria have been a focus of research, particularly due to their association with pathogenic microbes like *Mycobacterium tuberculosis, Corynebacterium diphtheriae, and Streptomyces scabies*. While they are often noted for their pathogenic species, the phylum Actinobacteria also include a wealth of beneficial microbes which play a crucial role in human well-being. These bacteria thrive in diverse environments—ranging from moderate to extreme conditions—and can be found as free-living organisms or as endoparasites. Moreover, they are among the largest producers of antibiotics, however their socio-economic impact is underscored. This review attempts to explore whether this phylum is ultimately a boon or bane to mankind.

1. Introduction

The filamentous Actinobacteria represent one of the largest phyla of Bacteria which derives its name from the Greek words *aktin* or *aktis* (ray) and *mukes* (fungi) (Barka et al., 2016). Traditionally due to their fungal morphology, they were considered the transition between fungi and bacteria. These include Gram-positive bacteria which follow a mycelial way of living and have a high G+C DNA content (ranging from 51% to more than 70%) (Świecimska et al., 2023; Tischler et al., 2019).

Actinobacteria are cosmopolitan in their distribution, most of them being free living and inhabiting both terrestrial and aquatic ecosystems. They are also known to inhabit extreme environments, for example, volcanic caves, hot springs, high mountains, and coral associations (Katti et al., 2022, Ventura et al., 2007). These ubiquitously distributed bacteria have been of great importance to mankind for their extensive production of secondary metabolites and derived antibiotics with antibacterial, anticancer, anthelmintic and antifungal properties (Liu et al., 2023, Anandan et al., 2016). These molecules have found phenomenal success in translational clinical research in the last few decades (Manikkam et al., 2024, Pongen et al., 2023, Mahajan et al., 2012). Several bioactive molecules produced by Actinobacteria are proven effective against drug resistant variants of the pathogen (Singh & Dubey, 2018). They also produce a plethora of other compounds that are significant for nematode control, carbon cycling, treatment of plant diseases, and degradation of organic matter. Despite such positive impacts, these bacteria are controversial because of their ability to cause diseases in both plants and animals, thereby questioning their merits. Through this review we discuss the various aspects of their habitat, biology, taxonomy, applications, and their exact role in natural ecosystems.

2. Habitat

Actinobacteria have a wide ecological distribution ranging from freshwaters, marine, terrestrial and extreme terrestrial dwellings.

2.1 Terrestrial ecosystems

Most Actinobacteria are saprophytic, soil dwelling bacteria (with genus *Streptomyces* being the most abundant) which are known to form symbiotic connections with the roots of plants (Dhanasekaran *et al.,* 2019). Actinobacterial ecology ranges from black-alkaline soil, sandy soil, sandy loam soil as well as in harsh conditions such as anoxic mangrove rhizospheres and desert soils (Jose *et al.,* 2021, Anbazhagan *et al*., 2017). Several terrestrial species produce novel antibiotics. The latest computational models have revealed a promising genomic potential of these bacteria for development of medicinally and agriculturally relevant bioactive compounds (Quinn & Dyson 2024). Studies have also reported that Actinobacteria living in soil become connected with surfaces such as fungal hyphae through polyketide synthesis (Krespach *et al*., 2023, Williams *et al*., 2002).

[1] Department of Zoology Shivaji College, University of Delhi, Raja Garden, New Delhi 110027, India
[2] Department of Zoology, Miranda House, University of Delhi, Delhi, 110007, India
[3] Department of Zoology, Maitreyi College, Bapu Dham, Chanakyapuri, New Delhi-110021, India
[4] Department of Zoology, University of Delhi, Delhi, 110007, India
[5] Department of Zoology, Sri Venkateswara College, University of Delhi, Delhi, 110021, India
[6] Department of Zoology, Hansraj College, University of Delhi, Delhi, 110007, India
#Authors have contributed equally *Correspondence: Dr. Mansi Verma mansiverma@hrc.du.ac.in; mansiverma20@gmail.com

These generally proliferate well in organic horizons (Hagedorn 1976) of soil and are also environmentally beneficial as they are found to degrade litter (Goodfellow & Williams, 1983). Generally, *Streptomycetes* are found in more arid and cooler soils (Guo et al., 2017). These also promote plant development by producing certain antifungal compounds and protect plants from root-borne pathogens (Hamby & Crawford, 2000). However certain Actinobacteria are also causative agents of various plant diseases such as *Streptomyces scabies* and *S. acidiscabies*., which are known to cause potato scab in plants (Ramezani-Moghadam et al., 2024, Takeuchi & Hatano, 1998). These positive and negative impacts of Actinobacteria keep their status controversial. The major Actinobacteria representatives found in soil include *Streptomycetes, Nocardia, Actinomadura, Nocardiopsis, Psudonocardia, Rhodococcus, Micromonospora* (Motallebirad et al., 2023, James et al., 2023, Anandan et al., 2016).

Actinobacteria form a bulk of microbial biomass in the rhizosphere and rhizoplane. Apart from nitrogen-fixation, they produce a huge spectrum of secondary metabolites, plant-growth promoting factors, and bio-active compounds which help in fighting infections caused by bacteria, fungi, viruses, etc. (Kavya et al., 2024). Such actinobacterial associations also help in reducing plant stress caused by salinity, drought, heavy metals, and temperature.

2.2 Aquatic Ecosystems

Actinobacteria show widespread distribution in aquatic habitats and are present in both freshwater and marine ecosystems.

2.2.1 Freshwater

Many types of Actinobacteria such as *Rhodococcus, Streptomyces, Micromonospora, Thermoactinomyces* can be readily isolated from freshwater sites (Mukhopadhyay & Biswas 2024; Cross, 1981). According to various reports, *Micromonospora* is predominant in aquatic habitats especially in lakes with deeper trophic states and fluctuating pH, oxygen and salinity levels (Liu et al., 2023). Some of the freshwater representatives act as natural degraders and recyclers, thereby modifying environmental conditions by active secretion of bioactive compounds. Hydrophobic spores and hyphae of Actinobacteria at water/air interfaces also play a major role in causing an increase in their populations. Some other Actinobacteria inhabiting freshwaters include *Arthrobacter, Corynebacterium, and Nocardia, Actinomadura madurae, Mycobacterium kansasii* (Anandan et al., 2016).

2.2.2 Marine

Marine ecosystems have greater biodiversity of Actinobacteria as compared to freshwater ecosystems and a large part of marine actinobacterial diversity has still remained untapped (Debbab et al, 2016). Some prominent genera of marine ecosystem include *Rhodococcus, Streptomyces, Salinispora, Dietzia, Salinibacterium, Aeromicrobium, Verrucosispora* (Setiawan et al., 2024; Ribeiro et al., 2023). Isolates have also been reported from extreme harsh anaerobic conditions at sub-zero temperatures on the deep sea floors as well as from highly acidic conditions near the hydrothermal vents (Orcutt et al., 2011).

2.3 Air Borne Actinobacteria

The air-borne spores produced by the members of the genera *Saccharopolyspora*, *Streptomyces*, and *Thermoactinomyces* circulate in the air and cause respiratory distress (Marchand et al., 2024). These are responsible for hypersensitivity pneumonitis commonly called farmer's or mushroom worker's lung and several other diseases (Guo et al., 2017; Qin et al., 2016). These actinobacterial spores are formed by the subdivision of existing hyphae and have a sheath around them for their effective circulation (van Bergeijk et al., 2020, Barka et al., 2016, Jensen et al., 2007).

2.4 Endophytic Actinobacteria

There are some Actinobacteria which inhabit the internal parts of various plants. These endophytic Actinobacteria do not cause any damage to the plants but rather provide advantages like protecting the plant against infectious diseases (Kaari et al., 2023, Yadav et al., 2018, Benson & Silvester, 1993). Further some endophytic Actinobacteria also belong to genera like *Streptoverticillium, Microbispora, Kibdelosporangium, Brevibacterium, Actinomadura, Glycomyces Plantactinospora, Polymorphospora* among others (Hui et al., 2021, Anandan et al., 2016).

2.4 Gut Actinobacteria

Apart from the above-mentioned habitats, Actinobacteria also tend to inhabit the gut of certain vertebrates such as in the gut of marine fishes the Indian mackerel and *Panna croaker* and invertebrates including some sponges, corals and molluscs (James et al., 2023; Hassan et al., 2017). They are present as symbiotic associations that help the organism in detoxification, and provide nutrition and protection against various infectious diseases. These gut

dwelling Actinobacteria include *Streptomyces*, *Nocardiopsis*, and *Oerskovia* (Tan et al. 2009). Further many *Streptomyces* sp. have been isolated from infected gut samples of chickens and goats (Kandasamy et al., 2016).

2.5 Actinobacteria growing on Compost and Mouldy Fodder

An environment with clammy, aerobic, and alkaline pH conditions provides home to a large number of Actinobacteria with a predominance of *Streptomycetes thermovulgaris, S. macrosporus, S. thermoviolaceus, S. megasporus and S. thermolineatus* (Donald et al., 2022, Girard et al., 2013). The abundance of Actinobacteria in fertilizers and animal feed such as straw and grains (Kallapiran & Kannan 2022, Lacey & Crook, 1988) is explained by the presence of high organic contents (Jensen et al., 2007).

2.6 Extreme Habitats

Actinobacteria proliferate well in various extreme conditions of temperature, pH, salinity, nutrients and radiations (Zenova et al., 2011) which is indicative of their physiological and metabolic flexibilities (Shivlata & Satyanarayana, 2015). They have also been isolated from gastrointestinal tracts of arthropods and millipedes as well as from their faecal matter (Jensen et al., 2007). Extremophilic Actinobacteria includes *Streptomycetes*, *Micromonospora*, *Rhodococcus* sp. (McCarthy & Williams, 1990).

3. Biology of Actinobacteria

Actinobacteria are predominantly saprophytic, most abundantly present in the soil in the form of semi-dormant spores for a large part of their lives, especially under limiting nutrient conditions (Williams et al., 2002). These thrive at high population densities (10^6 to 10^9 cells per gram of soil) in organic material rich soils (Goodfellow et al., 2015). Their density is also dependent upon temperature, pH, soil moisture and climatic conditions. Most of the Actinobacteria are mesophilic i.e. their optimal temperatures for growth varies from 25-30°C, however thermophilic Actinobacteria are exceptions as their optimal temperatures for growth ranges between 50°C and 60°C (Edwards, 1993). The growth of Actinobacteria in soil is also favoured when the humidity is low. However, in dry soils the Actinobacterial growth can become very limited or may even halt (Barka et al., 2016). Actinobacteria are known to grow best at pH levels ranging between 6 and 9 although they show an optimal growth at neutral pH (Anandan et al., 2016). However, actinobacteria (mostly *Streptomyces*) have also been isolated from sites (acidic soil) where the pH levels were as low as 3.5 (Kim et al., 2003).

4. Taxonomy of Actinobacteria

The evolutionary origin of Actinobacteria can be dated back to 2.7 billion years ago (Lewin et al., 2016). Phylum Actinobacteria remains the most fascinating of all prokaryotic phylums due to its vast diversity, ranging from antibiotic producing *Streptomyces* sp. to human disease causing *Mycobacterium* sp. The classification of prokaryotes, including Actinobacteria, has undergone significant modifications as a result of the polyphasic taxonomy (Brenner et al., 2005b,c). Currently, phylum Actinobacteria contains six classes Actinobacteria, Acidimicrobiia, Coriobacteriia, Nitriliruptoria, Rubrobacteria, Thermoleophilia (Wellington et al. , 1992; Gtari et al., 2012; Goodfellow et al., 2015; Guo et al., 2017; Zhi, Li, & Stackebrandt, 2009; Gao & Gupta, 2012; Ludwig et al., 2012; Foesel et al., 2016). Earlier, this phylum was identified by its branching position in 16S rRNA gene trees; however these sequences were unable to discriminate between closely related species, making it difficult to determine their evolutionary relationships and therefore generating ambiguity (Omura et al., 1982; Zhang et al., 1997). Other than 16S rRNA genes, genetic markers like RpoB, GyrB, DnaK, GrpE have been used for the construction of phylogenetic trees (Guo et al., 2017). However these markers are limited only to a particular group and result in unstable phylogenetic reconstructions (Alam, 2010; Rokas, 2003). "True" evolutionary relationships between the members of the bacterial members have been established due to the availability of whole genome sequences. However, this is also conflicting because of the varying evolutionary histories of genomes (Snel et al., 2005); though studies like Verma et al. (2013) have provided valuable insights on the phylogenetic relationships of Actinobacteria using consensus tree based approach.

5. Uses of Actinobacteria

5.1 Why are Actinobacteria considered a boon?

Actinobacteria have various applications commercially, pharmacologically, biotechnologically and ecologically. These applications are as follows:

5.1.1 Carbon cycling: Actinobacteria such as *Streptomyces* sp. are known to fix carbon in environments having leaf litter, dead and decaying matter, compost etc.

Additionally, they support the cycling of other carbon sources including chitin, which is a key component of the exoskeletons of invertebrates and fungi (Lewin et al., 2016). Actinobacteria are also known to cause the breakdown of cellulose, lignin, crystalline cellulose, hydrocarbons and other organic contaminants (Shivlata & Satyanarayana, 2015).

5.1.2 Symbiotic relations formed by Actinobacteria

Though Actinobacteria are mostly known to be free-living, they have also been observed to be symbionts with other eukaryotes generally in their gut or on external surfaces (Lewin et al., 2016). For example: *Corynebacterium* and *Bifidobacterium* are associated with insects, mammals as well as humans (Turroni et al., 2012). Apart from this, Actinobacteria also associated with endophytes and various other plants. Generally, their role as symbionts is in defence and providing nutrition to the host (Benson & Silvester, 1993; Conn et al., 2008)

5.1.3 Antimicrobial and Antifungal properties

Compared to cyanobacteria or any other kind of bacteria, Actinobacteria have been observed to be the most frequent producers of specialized metabolites (Sayed et al., 2020). Actinobacteria's antibacterial and antifungal characteristics stem from their capacity to generate a variety of secondary metabolites, which are mostly used in the production of compounds intended for human consumption, including antibiotics. They generate around 55% of all known antibiotics, making them the biggest producers of antibiotics among all bacteria (Anbazhagan et al., 2017). Around 589 molecules with diverse chemical structure have been isolated from Actinobacteria between 2015 to 2020 of which more than 50% have been reported to have the property of being biologically active (Jose et al., 2021). The majority of these antibiotics that are currently in use have been isolated from Actinobacteria, primarily belonging to the genera *Micromonospora* and *Streptomyces* (Jensen, Dwight, & Fenical, 1991*). Streptomyces*, the largest antibiotic-producing genus, generates over two-thirds of clinically used natural antibiotics derived from their diverse secondary metabolites (Anandan et al., 2016). They are also known to produce antifungals such as natamycin produced by *S. natalensis*, amphotericin B made by *S. nodosus,* nystatin produced by *S. noursei* among others. They also produce a large variety of antibiotics, such as the aminoglycoside class of antibiotics, which consists of cyclohexyl rings joined by glycosidic bonds and substituted with amine groups. Some novel antibiotics include Streptomycin produced by *S. griseus*, erythromycin produced by *S. erythraea* which is a great substitute for penicillin for those allergic to it , chloramphenicol produced by *S. venezuelae* used to treat various infections, tetracycline produced by *S. rimosus* used to treat skin conditions like acne. In view of their high toxicity, some antibiotics made by *Streptomyces* sp. are used as chemotherapeutic medications instead of being prescribed to humans as antibiotics (Burg et al., 1979). The rare and difficult to culture Actinobacteria harnessed from desert have been reported to produce bioactive compounds that pharmaceutical companies can use (Selim et al., 2021). The increase in resistance to antibiotics in microbial diversity has made it necessary to find and extract novel bioactive substances with potential as antibiotics. A recent study by Yang et al., 2024 has used a metagenomic approach along with CARD (The Comprehensive Antibiotic Resistance Database) to mine the microbial diversity in extreme environments of Karamay Gobi region. They were able to identify 30 actinobacterial species with antibiotic gene clusters with therapeutic properties which hold potential for new sets of drugs. More such compounds isolated from Actinobacteria with medicinal properties have been tabulated in Table 1.

Table 1: Medicinal compounds produced by Actinobacteria

Compound	Application	Actinobacteria	Family	References
1,8-Dihydroxy-2-ethyl-3 methylanthraquinone	Antitumor	*Streptomyces sp.*	Streptomycetaceae	(Huang et al., 2006)
1-Hydroxy-1-norresistomycin	Antibacterial	*Schisandra chinensis*	Schisandraceae	(Gorajana et al., 2005)
2-Allyloxyphenol	Antibacterial	*Streptomyces sundarbansensis*	Streptomycetaceae	(Arumugam et al., 2011)
Arenimycin	Antibacterial	*S. arenicola*	Arenicolidae	(Asolkar et al., 2010)
Bisanthraquinone	Antibacterial	*Streptomyces* sp.	Streptomycetaceae	(Nicolaou et al., 2009)

Carboxamycin	Antibacterial	*Streptomyces* sp.	Streptomycetaceae	(Hohmann et al., 2009)
Butenolides	Antitumor	*Streptoverticillium luteoverticillatum*	Streptomycetaceae	(Li et al., 2006)
Chinikomycins	Anticancer	*Streptomyces* sp.	Streptomycetaceae	(Li et al., 2005)
Chloramphenicol	Antibacterial	*Streptomyces venezuelae*	Streptomycetaceae	(Sekurova et al.,2016)
Marinomycins A–D	Anticancer	*Marinispora*	Streptomycetaceae	(Kwon et al., 2006)
Frigocyclinone	Antibacterial	*S. griseus*	Streptomycetaceae	(Bruntner et al., 2005)
Daryamides	Antifungal	*Streptomyces sp.*	Streptomycetaceae	(Asolkar et al., ,2006)
Hygromycin	Immunosupressive	*Streptomyces hygroscopicus*	Streptomycetaceae	(Palaniappan, Ayers, Gupta, Habib el, & Reynolds, 2006)
Lajollamycin	Antibacterial	*Streptomyces Nodosus*	Streptomycetaceae	(Manam et al., 2005)
Mitomycin C	Antitumor	*Streptomyces lavendulae*	Streptomycetaceae	(Sheldon et al., 1999)
Mechercharmycins	Anticancer	*Thermoactinomyces sp.*	Bacillaceae	(Kanoh et al., 2005)
Pacificanones A & B	Antibacterial	*S. pacifica*	Streptomycetaceae	(Oh et al..,2008)
Saliniketal	Cancer Chemoprevention	*S. arenicola*	Streptomycetaceae	(Wilson et al., 2010)
Piericidins	Antitumor	*Streptomyces sp*	Streptomycetaceae	(Hayakawa et al., 2007)
Proximicins	Antibacterial	*Verrucosispora sp.*	Micromonosporaceae	(Huang et al., 2016)
Rapamycin	Immunosupressive	*S. hygroscopicus*	Streptomycetaceae	(Dutta et al., 2014)
Salinosporamide B & C	Cytotoxicity	*S. tropica*	Streptomycetaceae	(Lechner et al., 2011)
Staurosporinone	Phycotoxicity	*Streptomyces sp.*	Streptomycetaceae	(Wu et al., 2006)
Streptokordin	Antitumor	*Streptomyces sp.*	Streptomycetaceae	(Jeong et al., 2006)
Streptomycin	Antibacterial	*S. griseus*	Streptomycetaceae	(Waksman, 1953)
Streptozotocin	Diabetogenic	*S. achromogenes*	Streptomycetaceae	(Eleazu et al., 2013)
Valinomycin	Ionophor	*S. griseus*	Streptomycetaceae	(Paananen et al., 2000)
ZHD-0501	Anticancer	*Actinomadura sp.*		*(*Olano et al., ,2009*)*
Tetracyclines	Antimicrobial	*Streptomyces achromogenes, Streptomyces Rimosus*	Streptomycetaceae	(Petkovic et al., 2017)

Tirandamycins	Antibacterial	*Streptomyces sp.*	Streptomycetaceae	(Carlson et al., 2009)
N-[2-hydroxyphenyl)-2-phenazinamine (NHP)	Antifungal	*Nocardia dassonvillei*	Nocardiopsaceae	(Gao et al., 2012)
Chromomycin B, A2, A3	Antitumor	*Streptomyces coelicolor*	Streptomycetaceae	(Menendez et al., 2004)
1,4-dihydroxy-2-(3-hydroxybutyl)-9, 10-anthraquinone 9, 10-anthrac	Antibacterial	*Streptomyces sp. RAUACT-1*	Streptomycetaceae	(Ravikumar et al., 2012)
Anthracyclines	Antitumor	*S. galileus*	Streptomycetaceae	(Hori et al., 1977)

5.1.4 Production of enzymes

Actinobacteria are capable of producing various enzymes (Table 2) which can degrade complex organic matter in soil or sediment (Ballav et al., 2012). They are the most crucial products synthesized by Actinobacteria after antibiotics (Nascimento et al., 2014). Some enzymes produced by them include amylases which play a role in extracellular digestion and have various biotechnological applications in textile, paper, fermentation and food industries because of their ability to digest starch (Pandey et al., 2000). Actinobacteria, bacteria, and fungi produce lipases that are very useful in the detergent, pharmaceutical, and diagnostic industries (Schmidt A. et al., 2005). *Streptomyces* is known to produce protease in its culture media (Sharmin et al., 2013). Actinobacteria have also been known to produce enzymes such as gelatinases, lecithinases, cellulases etc. (Gulve & Deshmukh, 2012).

Table 2: Enzymes produced by Actinobacteria

Enzyme	Actinobacteria	Family	Uses	References
Amylases	*Streptomyces sp., Streptomyces erumpens,Nocardiopsis sp. ,Thermobifida fusca, Nocardiopsis sp.*	Streptomycetaceae Nocardiopsaceae	Used in detergents, paper and textile industry, baking industry and for production of glucose and fructose syrups.	(Prakash et al., 2013)
Proteases	*Thermoactinomyces sp., Nocardiopsis sp., Streptomyces pactum, Streptomyces thermoviolaceus, Streptomyces sp*	Streptomycetaceae Nocardiopsaceae	Used in cheese making, brewing industry, leather indudtry, detergent industry, treatment of blood clots	(Prakash et al., 2013)
Lipases	*Streptomyces griseus*	Streptomycetaceae	Used in cheese flavouring, baking, textile and detergent industries	(Daza et al., 1990)
Cellulase	*Streptomyces sp., Thermobifida halotolerans , Streptomyces sp.*	Streptomycetaceae Thermomonosporaceae	Used in detergent, textile, paper and pulp industry	(Amore et al., 2012)
Xylanase	*Actinomadura sp.,*	Thermomonosporaceae	Used in animal feed and paper and pulp	(Chakdar et al.,

	Streptomyces sp.	Streptomycetaceae	industry	2016)
Pectinase	*Streptomyces lydicus*	Streptomycetaceae	It is used in scouring and textile industry	(Anandan et al., 2016)
L-Asparaginase	*S. griseus, Streptomyces karnatakensis, Streptomyces albidoflavus, and Nocardia sp.*	Streptomycetaceae Nocardiopsaceae	Used in chemotherapeutic drugs, food and baking industries	(Kavitha & Vijayalakshmi, 2012)
Glucose Oxidase	*Streptomyces coelicolor*	Streptomycetaceae	Baking industry	(Kwakman & Postma, 1994)
Phytase	*Streptomyces luteogriseus R10*	Streptomycetaceae	Used in phytate digestibility	(Anandan et al., 2016)
Keratinase	*Nocradiopsis sp. SD5*	Nocardiopsaceae	Used in animal feed	(Saha et al., 2013)

5.1.5 Bioherbicides

The secondary metabolites produced by Actinobacteria as discussed above can also be used for removing unwanted herbs or weeds from fields and gardens (Table 3). Herbicides produced by *Streptomyces saganonensis* are known to inhibit the growth of both dicotyledonous and monocotyledonous weeds. Anisomycin, which is produced by *Streptomyces* sp., inhibits the growth of a number of grassy weeds, including barnyardness. Actinobacteria also produces bialaphos, an important herbicide used to manage both annual and perennial grass weeds (Xiliang, 1994).

Table 3: Bioherbicides produced by Actinobacteria

Secondary metabolite	Actinobacteria	Family	Uses	References
Bialaphos	*Streptomyces viridochromogenes*	Streptomycetaceae	Controls growth of annual and perennial grasses	(Hara et al., 1991)
Anisomycin	*Streptomyces sp*	Streptomycetaceae	Growth inhibitor for annual grassy weeds	(Shen et al., 2019)
Carbocyclic Coformycin Hydantocidin	*Streptomyces hygroscopicus*	Streptomycetaceae	Can control several different types of weeds	(Nakajima et al., 1991)

5.1.6 Biosurfactants

Biosurfactants are bioactive compounds having hydrophobic and hydrophilic moieties (Marchant & Banat, 2012). In comparison to chemically obtained surfactants, the surfactants obtained from Actinobacteria are free of mineral oil, can be produced at low temperatures and are easily biodegradable (Anandan et al., 2016). They can be employed in a number of sectors, including mining, oil recovery, nutrition, textile, varnishing, and cosmetics (Marchant & Banat, 2012).

5.1.7 Bioweathering

Weathering is an important phenomenon in soil formation in which Actinobacteria play a major role because of their ability to survive in harsh conditions having limited nutrient content. Given their filamentous form and ability to thrive as oligotrophs, *Streptomyces* species are most frequently found at rock weathering sites. An important part of breaking down organic matter for soil formation is done by Actinobacteria. The species which bring about this include *Nocardioides, Kibdelosporangium, Arthrobacter, Knoellia, Brevibacterium, Rhodococcus* among others (Cockell et al., 2013).

5.1.8 Pigments

Actinobacteria are able to produce a wide range of pigments when grown in natural or synthetic media. These pigments are better as compared to synthetic dyes which require harmful chemicals for their production (Table 4). The colours of these pigments vary between red, blue, green, black etc. *Streptomyces* is generally known for producing such pigments which can be both bound to a cell or secreted in the medium, and the production is dependent on the factors shown in Figure 1 (Anandan et al., 2016).

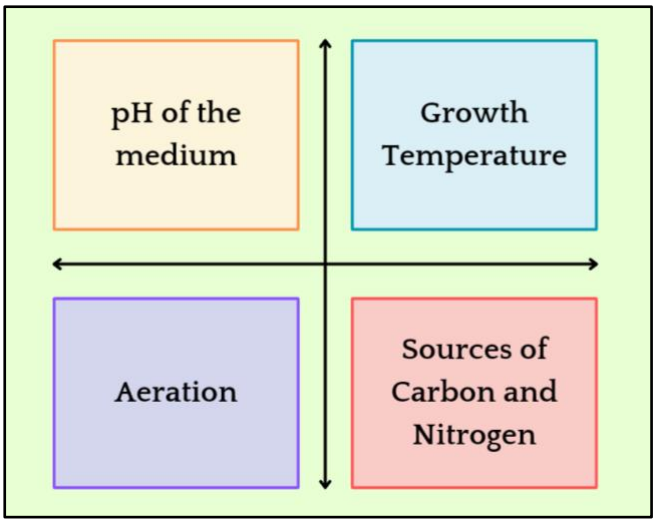

Figure 1. Factors affecting pigment production in *Streptomyces*

Table 4: Pigments produced by Actinobacteria

Pigment	Class	Actinobacteria	Family	References
Rhodomycin	Anthracycline glycoside	*Synodontis violaceus* DSM 40704	Mochokidae	(Holkar et al., 2013)
Actinomycin	Phenoxazinone	*Streptomyces* sp	Streptomycetaceae	(Barry et al., 1989)
Undecylprodigiosin Metacycloprodigiosin	Prodigiosin	*Streptomyces longispororuber* DSM 40599	Streptomycetaceae	(Darshan & Manonmani, 2015)
Granaticin	Naphthoquinone	*Streptomyces litmocidin* DSM 40164	Streptomycetaceae	(Elson et al., 1988)

5.1.9 Nanoparticle production

Nanoparticles are of great importance as they are used in the production of various materials. Actinobacterial species such as *Thermomonospora* sp., *Streptomyces aureofaciens, Streptomyces glaucus, Streptomyces viridogens* spp., *Streptomyces hygroscopicus, Nocardia farcinica* are known for producing gold nanoparticles (Ranjani et al., 2016). Similarly, various *Streptomyces* species are also involved in the production of copper, zinc, manganese and silver (Manivasagan et al., 2016) (Table 5).

Table 5: Nanoparticles produced by Actinobacteria

Actinobacteria	Family	Nanoparticles	References
Rhodococcus sp., *Streptomyces hygroscopicus, Streptomyces* sp., *Streptomyces rochei, Thermoactinomyces* sp., *Streptomyces albidoflavus, Nocardiopsis* sp.	Streptomycetaceae Bacillaceae Nocardiopsaceae Nocardiaceae	Silver	(Qi et al., 2019)
Streptomyces glaucus, Thermomonospora sp., *Streptomyces aureofaciens,*	Streptomycetaceae Bacillaceae	Gold	(Anandan et al., 2016)

Thermoactinomycete sp., *Streptomyces hygroscopicus, Nocardia farcinica, Streptomyces viridogens, Actinobacteria*			
Streptomyces sp.	Streptomycetaceae	Manganese, zinc, copper	(Qi et al., 2019)

5.1.10 Control of plant diseases

Though Actinobacteria are also a cause of various diseases in plants, they are known to treat a variety of them by production of various secondary metabolites. *Streptomyces* has been one of the major sources for the production of insecticides and herbicides (Tanaka & Omura, 1993). Kasugamycin is a metabolite that is generated by *Streptomyces kasugaensis*. It is a fungicidal and bactericidal agent that inhibits protein production (Umezawa et al., 1965). Kasugamycin is used for the control of diseases such as rice blast, diseases caused by bacterial *Pseudomonas* among others. Polyoxin B and D are another natural class of fungicides that are generated by *Streptomyces cacaoi* var. *asoensis* (Endo & Misato, 1969*)*. These polyoxins have the ability to interfere with chitin synthesis thereby interfering with fungal cell wall synthesis and are marketed to control fungal diseases in various plants, vegetables and ornamentals (Endo & Misato, 1969).

5.1.11 Nematode Control

Actinobacteria are involved in a variety of biological controls, including nematode control, because of their ability to produce antibiotics. Nematicides were earlier used for this purpose; however they cause a wide range of damage to the environment. Therefore, the use of Actinobacteria provides a more environment-friendly and sustainable way of biological control (Ikeda & Omura, 1995).

5.1.12 Biosorption of heavy metals

Just like other bacteria and fungi, Actinobacteria participate in the biosorption of heavy metals such as chromium, lead, and cadmium from the polluted environment (El-Gendy & El-Bondkly, 2016).

5.1.13 Wastewater Treatment

Actinobacteria are not only important for the beneficial secondary metabolites they synthesize, but also for their ability to produce some chemically important compounds that help in degrading recalcitrant pollutants. Actinobacteria are known for their roles of degrading phenol and naphthalene which are important pollutants present in wastewater and thus their role in wastewater treatment is considered pivotal (Soler et al., 2018). Three Actinobacteria strains that have the ability to break down 17 pesticides have recently been discovered from wastewater plants in the east and north of Algeria. These strains show promise as effective agents for the bioremediation of waste water ecosystems (Boufercha et al., 2022).

Other Applications

In addition to the previously mentioned aspects, Actinobacteria are crucial for the synthesis of phytohormones, promoting plant growth, and biotransformation (Shivlata & Satyanarayana, 2015). Members of the Actinobacteria also have the potential to act as biocontrol agents and induce systemic resistance in plants via Ethylene pathway and Salicylic acid mediated mechanism (Ebrahimi--Zarandi et al., 2022). Several Actinobacterial members have been effectively used for the green technology of aquaculture bioaugmentation due to their distinct growth characteristics and varied metabolic attributes (Polti et al. 2014; Rathore et al. 2021; James et al. 2023). Not only this, they are also known to produce biotechnologically important compounds such as carotenoids, alkaloids, etc. (Ballav et al., 2012).

5.2 Why Actinobacteria are considered a bane?

Not all interactions with Actinobacteria have a positive impact. The symbiotic association with the host may also have a negative impact. Actinobacteria are known to be virulent pathogens to both plants and animals including humans. A look at the pathogenic effect of these strains will give us an insight into Actinobacteria as pathogens.

5.2.1 Plant Diseases

Actinobacteria as causal agents of plant pathogenicity is not a new discovery. The actinobacterial genus *Corynebacterium* has been linked to several plant diseases. *C. betae* causes wilt and leaf spot of red beet. Production of polysaccharides, hormones, and toxins by these Actinobacterial species results in

disease in the host plant (Anandan et al., 2016). The genus *Streptomyces* is also a virulent strain causing plant diseases. They share a pathogenicity island which helps them infect the higher plants causing potato scab. Other pathogens which belong to the Microbacteriaceae family, such as *Leifsonia xyli* infect sugarcane and cause ratoon stunting disease, *Clavibacter michiganensis* infects the xylem of the shoot causing plant wilting in alfalfa, corn, tomato, and potato. *Rhodococcus fascians* is a pathogen of dicotyledonous herbaceous plants causing leafy gall syndrome (Lewin et al., 2016) (Table 6).

Table 6: Major Plant diseases caused by Actinobacteria

Actinobacteria	Family	Name of disease	References
Arthrobacter ilicis	Micrococcaceae	Blight of holly	(Collins et al., 1981)
C. flaccumfaciens	Microbacteriaceae	Wilt of bean	(Osdaghi et al., 2020)
Clavibacter michiganensis subsp. insidiosus	Microbacteriaceae	Stunting and wilt in alfalfa	(X. Li et al., 2018)
Clavibacter michiganensis ssp. m ichiganensis	Microbacteriaceae	Canker of tomato	(Nandi et al., 2018)
Clavibacter michiganensis subsp. n ebraskensis	Mycobacteriaceae	Wilt and blight of corn	(Friskop et al., 2014)
C. oortii	Microbacteriaceae	Spot of tulip leaves	(Geesteranus 1969)
Corynebacterium sp.	Corynebacteriaceae	Stem canker leaf spot in poinsettia	(Wehlburg C., 1966)
Rathayibacter toxicus	Corynebacteriaceae	Cereal gumming	(Park et al., 2017)
Clavibacter michiganensis subsp. s epedonicus	Microbacteriaceae	Tuber rot of potato	(Baranauskaite & Vasinauskiene, 2001)
Rathayibacter toxicus	Microbacteriaceae	Bud proliferation and Galls and in blueberry plants	(Park et al., 2017)
Rhodococcus fascians,	Nocardiaceae	Fasciation of sweet pea	(Stes et al., 2013)
S. aureofaciens, S. flaveolus, S. griseus	Streptomycetaceae	Potato common scab	(Shi et al., 2019)
S. ipomoeae	Streptomycetaceae	Scab in sweet potato	(Guan et al., 2012)
S. scabies, Streptomyces sp.	Streptomycetaceae	Russet and common scab in sugar beet and potato	(Goyer & Beaulieu, 1997)

5.2.2 Human and Animal diseases

Actinobacteria are also known to cause a variety of diseases in humans. The genus *Mycobacterium* has plagued humans for a long time and is usually associated with immunocompromised patients. For instance, *M. leprae* causes leprosy, *M. tuberculosis* causes tuberculosis in humans and *M. marinum,* which was initially identified as an organism responsible for tuberculosis in fish in 1926, is now reported to cause skin disease in humans. The genus *Nocardia* is also known to cause diseases in immunocompromised patients. Disseminated nocardiosis in humans and animals is caused by spreading of infection through the brain, kidneys, joints, bones, soft tissues, and eyes. Though uncommon, *Nocardia* species are responsible for 1% to 2% of all documented cases of brain abscesses. According to Barka et al. (2016), *C. ulcerans* causes respiratory tract infections, *C. jeikeium* has been linked to bacterial endocarditis , and *Corynebactrium diphtheriae* causes diphtheria. *Dermatophilus congolensis* causes both streptothricosis and dermatophilosis (Hyslop, 1979),

while different Actinobacteria species, such as *A. madurae* and *Nocardia asteroids*, may cause actinomycetoma (Pinoy, 1913). Animal infections can also be caused by Actinobacteria. *Actinomyces bovis*, *Actinomyces israelii*, and *Arachnia propionica* are the causative agents of actinomycosis (Bollinger, 1981). Equine pneumonia is caused by *C. equi* (Murray et al., 1995). According to Solomon et al. (2020), *C. renale* is typically the cause of pyelonephritis in cattle. Bovine farcy, a chronic granulomatous inflammation of the skin and lymphatics in cattle, is caused by *M. farcinogenes* and *M. senegalense* (Hamid et al., 1991) (Table 7).

Table 7: Diseases caused by Actinobacteria in animals and humans

Disease	Actinobacteria	Family	References
Actinomycetoma	*N. otitidiscaviarum, A. madurae, Nippostrongylus brasiliensis, Streptomyces somaliensis, Pellerieri sp., Nocardia asteroides*	Streptomycetaceae Thermomonosporaceae Heligmonellidae	(Boiron et al., 1998)
Actinomycosis	*Arachnia propionica, Actinomyces bovis, Actinomyces israelii*	Actinomycetaceae	(Pine et al., 1981)
Bacterial kidney disease	*Renibacterium salmoninarium*	Micrococcaceae	(Jansson et al., 2008)
Bovine farcy	*Mycobacterium farcinogenes, Mycobacterium senegalense*	Mycobacteriaceae	(Hamid, 2014)
Dermatophilosis & streptothricosis	*Dermatophilis congolensis*	Dermatophilaceae	(Burd et al., 2007)
Diphtheria	*Corynebacterium diphtheria*	Corynebacteriaceae	(Hoskisson, 2018)
Endocarditis	*Rothia dentocariosa, Oerskovia turbata*	Micrococcaceae	(Reller et al., 1975)
Equine pneumonia	*Rhodococcus equi*	Nocardiaceae	(Cohen, 2014)
Hypersensitivity pneumonitis	*Thermoactinomyces vulgaris, Micropolyspora jaeni, Saccharomonospora viridis*	Pseudonocardiaceae Bacillaceae Pseudonocardiaceae	(Kurup & Fink, 1975)
Leprosy	*Mycobacterium leprae*	Mycobacteriaceae	(Noordeen, 1994)
Mycobacterioses	Many species of *Mycobacterium*	Mycobacteriaceae	(Lloret et al., 2013)
Pulmonary nocardiosis	*Nocardia asteroides, N. brasiliensis, Nocardiopsis dassonvillei*	Nocardiaceae	(J. W. Wilson, 2012)
Systemic nocardiosis	*N. brasiliensis, Nocardia asteroids*	Nocardiaceae	(J. W. Wilson, 2012)
Pyelonephritis in cattle	*Corynebacterium renale*	Corynebacteriaceae	(Hiramune et al., 1971)
Tuberculosis	*Mycobacterium tuberculosis*	Mycobacteriaceae	(Smith, 2003)
Purulent infections including abscesses	*Actinomyces, (Corynebacterium) pyogenes, Corynebacterium pseudotuberculosis*	Corynebacteriaceae	(Rzewuska et al., 2019)

5.2.3 Antibiotic Resistance

Recent times have shown that the spread of antibiotic resistance genes from Actinobacteria to pathogens posing a serious risk to human health (Parras et al, 2025). In addition to the antibiotic resistance genes they naturally carry, Actinobacteria can acquire antibiotic resistance genes from other Actinobacteria through horizontal gene transfer (D'Costa et al., 2006). Recent studies have suggested that horizontal gene transfer might be very common between Actinobacteria and Proteobacteria employing conjugative plasmids as carrier sequence, and this could be as a result of increased selection pressure brought on by the widespread use of antibiotics and mobile genetic elements including transposons, integrons, and conjugative plasmids, which are frequently clustered with genes that confer antibiotic resistance (Gillings, 2014).

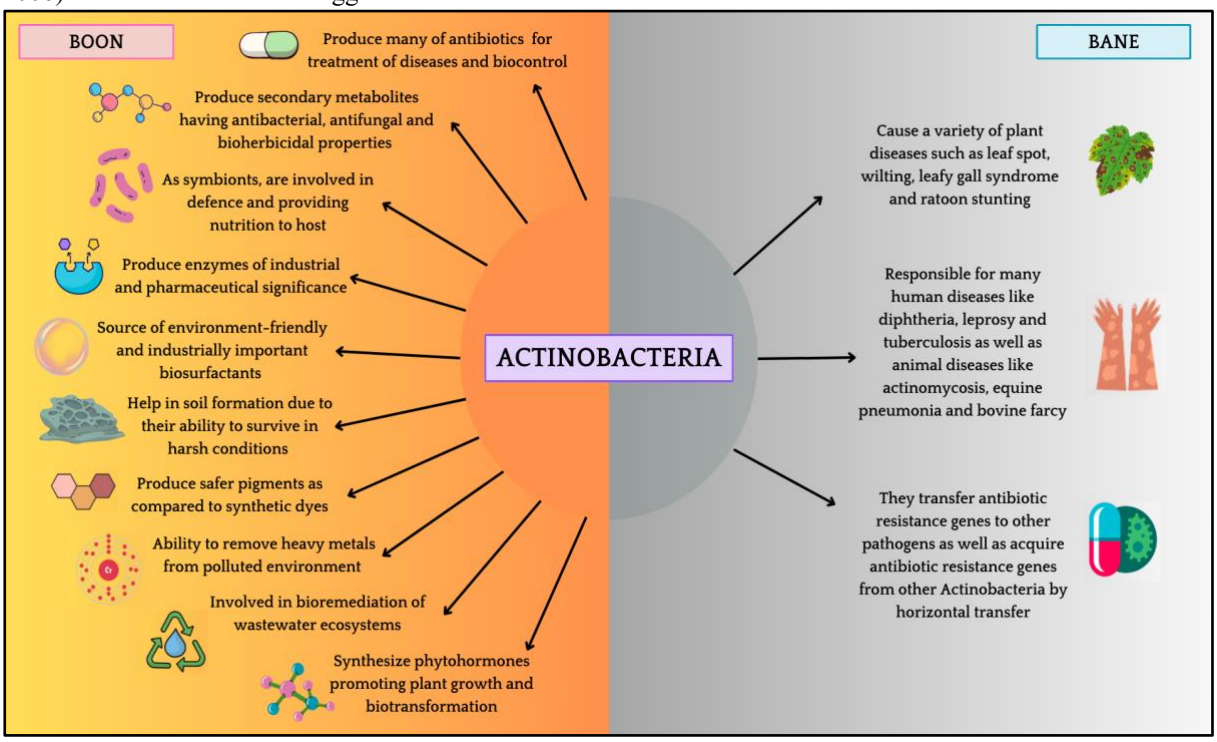

Figure 2. Comparison of Actinobacteria as a boon and as a bane

Overall, whether pathogenic or beneficial, Actinobacteria have long held socio-economic significance. Their impacts are multifaceted, involving healthcare costs, effects on agriculture, and vital roles in biotechnology and environmental health. They can be a medical boon and at the same time, their sister taxa could pose a threat to health (Figure 2).

Conclusion

Actinobacteria, play a significant role in pharmaceutical biotechnology benefiting mankind. Occupying diverse habitats from the harshest environments of dark caves to terrestrial as well as aquatic landscapes, these bacteria are often considered a boon because of the various positive impacts they possess on multitudes of organisms found on earth . These positive impacts include their roles in carbon cycling, biosorption of metals, treatment of plant diseases, bio-herbicide formation, antibiotic synthesis, nematode control among others. Not only this, researchers are also trying to tap into other potentials of Actinobacteria which can benefit mankind as a whole in the future. Nevertheless, these bacteria are also linked to the spread of diseases in humans, animals and plants, despite their numerous advantageous qualities. This is a major drawback because even though the positive impacts outnumber the negative ones, still the negative impacts can have effects which can not only interfere with the life of various living organisms but also threaten their existence. In such a scenario, commenting upon whether Actinobacteria are truly a boon or a bane becomes tough. However, if in future scientists and researchers find a way to overcome the negative impacts of these bacteria, only then can we truly call them a boon to mankind and completely acknowledge their credibility.

References

1. Alam, M. T., Merlo, M. E., Takano, E., & Breitling, R. (2010). Genome-based phylogenetic analysis of Streptomyces and its relatives. *Molecular phylogenetics and evolution*, *54*(3), 763-772.

2. Amore, A., Pepe, O., Ventorino, V., Birolo, L., Giangrande, C., & Faraco, V. (2012). Cloning and recombinant expression of a cellulase from the cellulolytic strain Streptomyces sp. G12 isolated from compost. *Microb Cell Fact, 11*, 164. doi:10.1186/1475-2859-11-164

3. Anandan, R., Dharumadurai, D., & Manogaran, G. P. (2016). An introduction to actinobacteria. In Actinobacteria-basics and biotechnological applications. IntechOpen.

4. Anbazhagan, S., Azeez, S., Morukattu, G., Rajan, R., Venkatesan, K., & Thangavelu, K. P. (2017). Synthesis, characterization and biological applications of mycosynthesized silver nanoparticles. 3 Biotech, 7, 1-9.

5. Arumugam, M., Mitra, A., Pramanik, A., Saha, M., Gachhui, R., & Mukherjee, J. (2011). Streptomyces sundarbansensis sp. nov., an actinomycete that produces 2-allyloxyphenol. International journal of systematic and evolutionary microbiology, 61(11), 2664-2669.

6. Asolkar, R. N., Jensen, P. R., Kauffman, C. A., & Fenical, W. (2006). Daryamides A− C, weakly cytotoxic polyketides from a marine-derived actinomycete of the genus Streptomyces strain CNQ-085. Journal of natural products, 69(12), 1756-1759.

7. Asolkar, R. N., Kirkland, T. N., Jensen, P. R., & Fenical, W. (2010). Arenimycin, an antibiotic effective against rifampin-and methicillin-resistant Staphylococcus aureus from the marine actinomycete Salinispora arenicola. The Journal of antibiotics, 63(1), 37-39.

8. Ballav, S., Dastager, S. G., & Kerkar, S. (2012). Biotechnological significance of Actinobacterial research in India. .

9. Baranauskaite, L., & Vasinauskiene, M. (2001). Bacterial ring rot of Potatoes caused by Clavibacter michiganensis subsp. sepedonicus in Lithuania. Plant Disease, 85(10), 1119-1119.

10. Barka, E.A., Vatsa, P., Sanchez, L., Gaveau-Vaillant, N., Jacquard, C., Klenk, H.P., Clément, C., Ouhdouch, Y. and van Wezel, G.P., (2016). Taxonomy, physiology, and natural products of Actinobacteria. Microbiology and molecular biology reviews, 80(1), 1-43.

11. Barry III, C. E., Nayar, P. G., & Begley, T. P. (1989). Phenoxazinone synthase: mechanism for the formation of the phenoxazinone chromophore of actinomycin. Biochemistry, 28(15), 6323-6333.

12. Benson, D. R., & Silvester, W. B. (1993). Biology of Frankia strains, actinomycete symbionts of actinorhizal plants. *Microbiol Rev, 57*(2), 293-319. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/8336669

13. Boiron, P., Locci, R., Goodfellow, M., Gumaa, S. A., Isik, K., Kim, B., . . . Shojaei, H. (1998). Nocardia, nocardiosis and mycetoma. *Med Mycol, 36 Suppl 1*, 26-37. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/9988489

14. Bollinger Braunde Al, Davis CE. Medical microbiology and infectious diseases. 2nd ed. Philadelphia: WB saunders Co; 1981. Ueber eine neue Pilzkrheit beim Rinde; pp. 391–392.

15. Boufercha, O., Moreira, I.S., Castro, P.M.L. *et al. Actinobacteria* isolated from wastewater treatment plants located in the east-north of Algeria able to degrade pesticides. *World J Microbiol Biotechnol* 38, 105 (2022)

16. Brenner, D. J., Krieg, N. R., Staley, J. T., and Garrity, G. M. (eds.). (2005b). Bergey's Manual of Systematic Bacteriology, Vol. 2, The Proteobacteria (Part B). 2nd Edn. New York, NY: Springer.

17. Brenner, D. J., Krieg, N. R., Staley, J. T., and Garrity, G. M. (eds.). (2005c). Bergey's Manual of Systematic Bacteriology, Vol. 2, The Proteobacteria (Part C), 2nd Edn. New York, NY: Springer.

18. Bruntner, C., Binder, T., Pathom-aree, W., Goodfellow, M., Bull, A. T., Potterat, O., . . . Fiedler, H. P. (2005). Frigocyclinone, a novel angucyclinone antibiotic produced by a Streptomyces griseus strain from Antarctica. *J Antibiot (Tokyo), 58*(5), 346-349. doi:10.1038/ja.2005.43

19. Burd, E. M., Juzych, L. A., Rudrik, J. T., & Habib, F. (2007). Pustular dermatitis caused by Dermatophilus congolensis. *J Clin Microbiol, 45*(5), 1655-1658. doi:10.1128/JCM.00327-07

20. Burg, R. W., Miller, B. M., Baker, E. E., Birnbaum, J., Currie, S. A., Hartman, R., . . . Omura, S. (1979). Avermectins, new family of potent anthelmintic agents: producing organism and fermentation. *Antimicrob Agents Chemother, 15*(3), 361-367. doi:10.1128/aac.15.3.361

21. Carlson, J. C., Li, S., Burr, D. A., & Sherman, D. H. (2009). Isolation and characterization of tirandamycins from a marine-derived Streptomyces sp. *J Nat Prod, 72*(11), 2076-2079. doi:10.1021/np9005597

22. Chakdar, H., Kumar, M., Pandiyan, K., Singh, A., Nanjappan, K., Kashyap, P. L., & Srivastava, A. K. (2016). Bacterial xylanases: biology to biotechnology. *3 Biotech, 6*(2), 150. doi:10.1007/s13205-016-0457-z

23. Cockell, C. S., Kelly, L. C., & Marteinsson, V. (2013). Actinobacteria - an ancient phylum active in volcanic rock weathering. *Geomicrobiol*.

24. Cohen, N. D. (2014). Rhodococcus equi foal pneumonia. *Vet Clin North Am Equine Pract, 30*(3), 609-622. doi:10.1016/j.cveq.2014.08.010

25. Collins, M. D., Jones, D., & Kroppenstedt, R. M. (1981). Reclassification of Corynebacterium ilicis (Mandel, Guba and Litsky) in the genus Arthrobacter, as Arthrobacter ilicis comb. nov. *Zentralblatt Für Bakteriologie Mikrobiologie Und Hygiene I Abt Originale C Allgemeine Angewandte Und Ökologische Mikrobiologie*, *2*(4), 318–323. https://doi.org/10.1016/s0721-9571(81)80024-5

26. Conn, V. M., Walker, A. R., & Franco, C. M. (2008). Endophytic actinobacteria induce defense pathways in Arabidopsis thaliana. *Mol Plant Microbe Interact, 21*(2), 208-218. doi:10.1094/MPMI-21-2-0208

27. Cross, T. (1981). Aquatic actinomycetes: a critical survey of the occurrence, growth and role of actinomycetes in aquatic habitats. *J Appl Bacteriol, 50*(3), 397-423. doi:10.1111/j.1365-2672.1981.tb04245.x

28. Darshan, N., & Manonmani, H. K. (2015). Prodigiosin and its potential applications. *J Food Sci Technol, 52*(9), 5393-5407. doi:10.1007/s13197-015-1740-4

29. Daza, A., Gil, J. A., Vigal, T., & Martin, J. F. (1990). Cloning and characterization of a gene of Streptomyces griseus that increases production of extracellular enzymes in several species of Streptomyces. *Mol Gen Genet, 222*(2-3), 384-392. doi:10.1007/BF00633844

30. D'Costa, V. M., McGrann, K. M., Hughes, D. W., & Wright, G. D. (2006). Sampling the antibiotic resistome. *Science, 311*(5759), 374-377. doi:10.1126/science.1120800

31. Dhanasekaran, D., Thajuddin, N., & Panneerselvam, A. (2019). *Antimicrobials: Synthetic and Natural Compounds* (Vol. 1).

32. Donald, L., Pipite, A., Subramani, R., Owen, J., Keyzers, R. A., & Taufa, T. (2022). Streptomyces: Still the biggest producer of new natural secondary metabolites, a current perspective. *Microbiology Research*, *13*(3), 418-465.

33. Dutta, S., Basak, B., Bhunia, B., Chakraborty, S., & Dey, A. (2014). Kinetics of rapamycin production by Streptomyces hygroscopicus MTCC 4003. *3 Biotech, 4*(5), 523-531. doi:10.1007/s13205-013-0189-2

34. Ebrahimi-Zarandi M, Saberi Riseh R, Tarkka MT. Actinobacteria as Effective Biocontrol Agents against Plant Pathogens, an Overview on Their Role in Eliciting Plant Defense. *Microorganisms*. 2022; 10(9):1739. https://doi.org/10.3390/microorganisms10091739

35. Eleazu, C. O., Eleazu, K. C., Chukwuma, S., & Essien, U. N. (2013). Review of the mechanism of cell death resulting from streptozotocin challenge in experimental animals, its practical use and potential risk to humans. *J Diabetes Metab Disord, 12*(1), 60. doi:10.1186/2251-6581-12-60

36. El-Gendy, M. M., & El-Bondkly, A. M. (2016). Evaluation and enhancement of heavy metals bioremediation in aqueous solutions by Nocardiopsis sp. MORSY1948, and Nocardia sp. MORSY2014. *Braz J Microbiol, 47*(3), 571-586. doi:10.1016/j.bjm.2016.04.029

37. Elson, A. L., Box, S. J., & Gilpin, M. L. (1988). New quinone antibiotics of the granaticin type, isolated from Streptomyces lateritius. I. Production, isolation and properties. *J Antibiot (Tokyo), 41*(4), 570-572. doi:10.7164/antibiotics.41.570

38. Endo, A., & Misato, T. (1969). Polyoxin D, a competitive inhibitor of UDP-N-acetylglucosamine: chitin N-acetylglucosaminyltransferase in Neurospora crassa. *Biochem Biophys Res Commun, 37*(4), 718-722. doi:10.1016/0006-291x(69)90870-5

39. Foesel, B. U., Geppert, A., Rohde, M., & Overmann, J. (2016). *Parviterribacter kavangonensis* gen. nov., sp. nov. and *Parviterribacter multiflagellatus* sp. nov., novel members of *Parviterribacteraceae* fam. nov. within the order *Solirubrobacterales*, and emended descriptions of the classes *Thermoleophilia* and *Rubrobacteria* and their orders and families. *International journal of systematic and evolutionary microbiology*, *66*(2), 652–665. https://doi.org/10.1099/ijsem.0.000770

40. Friskop, A., Kinzer, K., McConnell, M., Liu, Z., Korus, K., Timmerman, A., & Jackson, T. (2014). First Report of Goss's Bacterial Leaf Blight and Wilt of Corn Caused by Clavibacter michiganensis subsp. nebraskensis in North Dakota. *Plant Dis, 98*(12), 1739. doi:10.1094/PDIS-04-14-0397-PDN

41. Gao, B., & Gupta, R. S. (2012). Phylogenetic framework and molecular signatures for the main clades of the phylum Actinobacteria. *Microbiol Mol Biol Rev, 76*(1), 66-112. doi:10.1128/MMBR.05011-11

42. Gao, X., Lu, Y., Xing, Y., Ma, Y., Lu, J., Bao, W., . . . Xi, T. (2012). A novel anticancer and antifungus

phenazine derivative from a marine actinomycete BM-17. *Microbiol Res, 167*(10), 616-622. doi:10.1016/j.micres.2012.02.008

43. Geesteranus, G. J. S. H. P. M. (1969). A new disease in tulip caused by Corynebacterium oortii nov. spec. *Netherlands Journal of Plant Pathology volume*. doi:https://doi.org/10.1007/BF02137204

44. Gillings, M. R. (2014). Integrons: past, present, and future. *Microbiol Mol Biol Rev, 78*(2), 257-277. doi:10.1128/MMBR.00056-13

45. Girard, G., Traag, B. A., Sangal, V., Mascini, N., Hoskisson, P. A., Goodfellow, M., & van Wezel, G. P. (2013). A novel taxonomic marker that discriminates between morphologically complex actinomycetes. *Open Biol, 3*(10), 130073. doi:10.1098/rsob.130073

46. Goodfellow, M., & Williams, S. T. (1983). Ecology of actinomycetes. *Annu Rev Microbiol, 37*, 189-216. doi:10.1146/annurev.mi.37.100183.001201

47. Goodfellow, M., Sangal, V., Jones, A. L., & Sutcliffe, I. C. (2015). Charting stormy waters: A commentary on the nomenclature of the equine pathogen variously named Prescottella equi, Rhodococcus equi and Rhodococcus hoagii. *Equine Vet J, 47*(5), 508-509. doi:10.1111/evj.12399

48. Gorajana, A., Kurada, B. V., Peela, S., Jangam, P., Vinjamuri, S., Poluri, E., & Zeeck, A. (2005). 1-Hydroxy-1-norresistomycin, a new cytotoxic compound from a marine actinomycete, Streptomyces chibaensis AUBN1/7. *J Antibiot (Tokyo), 58*(8), 526-529. doi:10.1038/ja.2005.72

49. Goyer, C., & Beaulieu, C. (1997). Host Range of Streptomycete Strains Causing Common Scab. *Plant Dis, 81*(8), 901-904. doi:10.1094/PDIS.1997.81.8.901

50. Gtari, M., Ghodhbane-Gtari, F., Nouioui, I., Beauchemin, N., & Tisa, L. S. (2012). Phylogenetic perspectives of nitrogen-fixing actinobacteria. *Arch Microbiol, 194*(1), 3-11. doi:10.1007/s00203-011-0733-6

51. Guan, D., Grau, B. L., Clark, C. A., Taylor, C. M., Loria, R., & Pettis, G. S. (2012). Evidence that thaxtomin C is a pathogenicity determinant of Streptomyces ipomoeae, the causative agent of Streptomyces soil rot disease of sweet potato. *Mol Plant Microbe Interact, 25*(3), 393-401. doi:10.1094/MPMI-03-11-0073

52. Gulve, R., & Deshmukh, A. (2012). Antimicrobial activity of the marine actinomycetes. *International Multidisciplinary Research Journal*.

53. Guo, J., Wang, A., Yang, K., Ding, H., Hu, Y., Yang, Y., . . . Xin, Z. (2017). Isolation, characterization and antimicrobial activities of polyacetylene glycosides from Coreopsis tinctoria Nutt. *Phytochemistry, 136*, 65-69. doi:10.1016/j.phytochem.2016.12.023

54. Hagedorn, C. (1976). Influences of soil acidity on Streptomyces populations inhabiting forest soils. *Appl Environ Microbiol, 32*(3), 368-375. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/10835

55. Hamby, M. K., & Crawford, D. L. (2000). The enhancement of plant growth by selected Streptomyces species. *American Society for Microbiology*.

56. Hamid, M. E. (2014). Current Perspectives on Mycobacterium farcinogenes and Mycobacterium senegalense, the Causal Agents of Bovine Farcy. *Vet Med Int, 2014*, 247906. doi:10.1155/2014/247906

57. Hamid, M.E., G.E. Mohamed, M.T. Abu-Samra, S.M. El-Sanousi, M.E. Barri, Bovine farcy: A clinico-pathological study of the disease and its aetiological agent, Journal of Comparative Pathology, 105 (3), 1991, 287-301,0021-9975, https://doi.org/10.1016/S0021-9975(08)80197-1.

58. Hara, O., Murakami, T., Imai, S., Anzai, H., Itoh, R., Kumada, Y., . . . et al. (1991). The bialaphos biosynthetic genes of Streptomyces viridochromogenes: cloning, heterospecific expression, and comparison with the genes of Streptomyces hygroscopicus. *J Gen Microbiol, 137*(2), 351-359. doi:10.1099/00221287-137-2-351

59. Hassan, S. S., Anjum, K., Abbas, S. Q., Akhter, N., Shagufta, B. I., Shah, S. A., & Tasneem, U. (2017). Emerging biopharmaceuticals from marine actinobacteria. *Environmental toxicology and pharmacology*, *49*, 34–47. https://doi.org/10.1016/j.etap.2016.11.015.

60. Hayakawa, Y., Shirasaki, S., Shiba, S., Kawasaki, T., Matsuo, Y., Adachi, K., & Shizuri, Y. (2007). Piericidins C7 and C8, new cytotoxic antibiotics produced by a marine Streptomyces sp. *J Antibiot (Tokyo), 60*(3), 196-200. doi:10.1038/ja.2007.22

61. Hiramune, T., Inui, S., Murase, N., & Yanagawa, R. (1971). Virulence of three types of Corynebacterium renale in cows. *Am J Vet Res, 32*(2), 237-242. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/5545463

62. Hohmann, C., Schneider, K., Bruntner, C., Irran, E., Nicholson, G., Bull, A. T., . . . Fiedler, H. P. (2009). Caboxamycin, a new antibiotic of the benzoxazole family produced by the deep-sea strain Streptomyces sp. NTK 937. *J Antibiot (Tokyo), 62*(2), 99-104. doi:10.1038/ja.2008.24

63. Holkar, S., Begde, D., Nashikkar, N., Kadam, T., & Upadhyay, A. (2013). Rhodomycin analogues from Streptomyces purpurascens: isolation, characterization

and biological activities. *Springerplus, 2*(1), 93. doi:10.1186/2193-1801-2-93

64. Hori, S., Shirai, M., Hirano, S., Oki, T., Inui, T., Tsukagoshi, S., . . . Umezawa, H. (1977). Antitumor activity of new anthracycline antibiotics, aclacinomycin-A and its analogs, and their toxicity. *Gan, 68*(5), 685-690. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/579346

65. Hoskisson, P. A. (2018). Microbe Profile: Corynebacterium diphtheriae - an old foe always ready to seize opportunity. *Microbiology (Reading), 164*(6), 865-867. doi:10.1099/mic.0.000627

66. Huang, P., Xie, F., Ren, B., Wang, Q., Wang, J., Wang, Q., . . . Zhang, L. (2016). Anti-MRSA and anti-TB metabolites from marine-derived Verrucosispora sp. MS100047. *Appl Microbiol Biotechnol, 100*(17), 7437-7447. doi:10.1007/s00253-016-7406-y

67. Huang, Y. F., Tian, L., Fu, H. W., Hua, H. M., & Pei, Y. H. (2006). One new anthraquinone from marine Streptomyces sp. FX-58. *Nat Prod Res, 20*(13), 1207-1210. doi:10.1080/14786410600899142

68. Hui, M.L.Y., Tan, L.T.H., Letchumanan, V., He, Y.W., Fang, C.M., Chan, K.G., Law, J.W.F. and Lee, L.H., (2021). The extremophilic actinobacteria: from microbes to medicine. Antibiotics, 10(6), 682.

69. Hyslop N. S. (1979). Dermatophilosis (streptothricosis) in animals and man. *Comparative immunology, microbiology and infectious diseases*, *2*(4), 389–404. https://doi.org/10.1016/0147-9571(79)90082-1

70. Ikeda, H., & Omura, S. (1995). Control of avermectin biosynthesis in Streptomyces avermitilis for the selective production of a useful component. *J Antibiot (Tokyo), 48*(7), 549-562. doi:10.7164/antibiotics.48.549

71. James, G., Prasannan Geetha, P., Thavarool Puthiyedathu, S., & Vattringal Jayadradhan, R. K. (2023). Applications of Actinobacteria in aquaculture: prospects and challenges. *3 Biotech*, *13*(2), 42.

72. Jansson, E., Lindberg, L., Saker, E., & Aspan, A. (2008). Diagnosis of bacterial kidney disease by detection of Renibacterium salmoninarum by real-time PCR. *J Fish Dis, 31*(10), 755-763. doi:10.1111/j.1365-2761.2008.00949.x

73. Jensen, P. R., Dwight, R., & Fenical, W. (1991). Distribution of actinomycetes in near-shore tropical marine sediments. *Appl Environ Microbiol, 57*(4), 1102-1108. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/2059035

74. Jensen, P. R., Williams, P. G., Oh, D. C., Zeigler, L., & Fenical, W. (2007). Species-specific secondary metabolite production in marine actinomycetes of the genus Salinispora. *Appl Environ Microbiol, 73*(4), 1146-1152. doi:10.1128/AEM.01891-06

75. Jeong, S. Y., Shin, H. J., Kim, T. S., Lee, H. S., Park, S. K., & Kim, H. M. (2006). Streptokordin, a new cytotoxic compound of the methylpyridine class from a marine-derived Streptomyces sp. KORDI-3238. *J Antibiot (Tokyo), 59*(4), 234-240. doi:10.1038/ja.2006.33

76. Jose, P. A., Maharshi, A., & Jha, B. (2021). Actinobacteria in natural products research: Progress and prospects. *Microbiological research*, *246*, 126708.

77. Kaari, M., Manikkam, R., Annamalai, K. K., & Joseph, J. (2023). Actinobacteria as a source of biofertilizer/biocontrol agents for bio-organic agriculture. Journal of Applied Microbiology, 134(2), lxac047.

78. Kallapiran, K. A., & Kannan, R. (2022). A review on the agricultural waste residues management by different microbes. *Journal of Agriculture and Ecology Research International*, 93-113.

79. Kandasamy, S., Muthusamy, G., Balakrishnan, S., Duraisamy, S., Thangasamy, S., Seralathan, K. K., & Chinnappan, S. (2016). Optimization of protease production from surface-modified coffee pulp waste and corncobs using Bacillus sp. by SSF. *3 Biotech, 6*(2), 167. doi:10.1007/s13205-016-0481-z

80. Kanoh, K., Matsuo, Y., Adachi, K., Imagawa, H., Nishizawa, M., & Shizuri, Y. (2005). Mechercharmycins A and B, cytotoxic substances from marine-derived Thermoactinomyces sp. YM3-251. *J Antibiot (Tokyo), 58*(4), 289-292. doi:10.1038/ja.2005.36

81. Katti, A. K. S., AK, S., & Mudgulkar, S. B. (2022). Diversity and classification of rare actinomycetes. In Actinobacteria: Ecology, Diversity, Classification and Extensive Applications (pp. 117-142). Singapore: Springer Nature Singapore.

82. Kavitha, A., & Vijayalakshmi, M. (2012). A study on L-asparaginase of Nocardia levis MK-VL_113. *ScientificWorldJournal, 2012*, 160434. doi:10.1100/2012/160434

83. Kavya, T., Govindasamy, V., Suman, A., & Abraham, G. (2024). Plant–Actinobacteria Interactions for Biotic and Abiotic Stress Management in Crops. In *Plant Holobiome Engineering for Climate-Smart Agriculture* (pp. 441-463). Singapore: Springer Nature Singapore.

84. Kim, S. B., Lonsdale, J., Seong, C. N., & Goodfellow, M. (2003). Streptacidiphilus gen. nov., acidophilic actinomycetes with wall chemotype I and emendation of the family Streptomycetaceae (Waksman and Henrici (1943)AL) emend. Rainey et al. 1997. *Antonie*

Van Leeuwenhoek, 83(2), 107-116. doi:10.1023/a:1023397724023

85. Krespach, M.K., Stroe, M.C., Netzker, T., Rosin, M., Zehner, L.M., Komor, A.J., Beilmann, J.M., Krüger, T., Scherlach, K., Kniemeyer, O. and Schroeckh, V., (2023). Streptomyces polyketides mediate bacteria–fungi interactions across soil environments. Nature Microbiology, 8(7), 1348-1361.

86. Kurup, V. P., & Fink, J. N. (1975). A scheme for the identification of thermophilic actinomycetes associated with hypersensitivity pneumonitis. *J Clin Microbiol, 2*(1), 55-61. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/1225928

87. Kwakman, J. H., & Postma, P. W. (1994). Glucose kinase has a regulatory role in carbon catabolite repression in Streptomyces coelicolor. *J Bacteriol, 176*(9), 2694-2698. doi:10.1128/jb.176.9.2694-2698.1994

88. Kwon, H. C., Kauffman, C. A., Jensen, P. R., & Fenical, W. (2006). Marinomycins A-D, antitumor-antibiotics of a new structure class from a marine actinomycete of the recently discovered genus "marinispora". *J Am Chem Soc, 128*(5), 1622-1632. doi:10.1021/ja0558948

89. Lechner, A., Eustaquio, A. S., Gulder, T. A., Hafner, M., & Moore, B. S. (2011). Selective overproduction of the proteasome inhibitor salinosporamide A via precursor pathway regulation. *Chem Biol, 18*(12), 1527-1536. doi:10.1016/j.chembiol.2011.10.014

90. Lewin, G. R., Carlos, C., Chevrette, M. G., Horn, H. A., McDonald, B. R., Stankey, R. J., . . . Currie, C. R. (2016). Evolution and Ecology of Actinobacteria and Their Bioenergy Applications. *Annu Rev Microbiol, 70*, 235-254. doi:10.1146/annurev-micro-102215-095748

91. Li, D. H., Zhu, T. J., Liu, H. B., Fang, Y. C., Gu, Q. Q., & Zhu, W. M. (2006). Four butenolides are novel cytotoxic compounds isolated from the marine-derived bacterium, Streptoverticillium luteoverticillatum 11014. *Arch Pharm Res, 29*(8), 624-626. doi:10.1007/BF02968245

92. Li, F., Maskey, R. P., Qin, S., Sattler, I., Fiebig, H. H., Maier, A., . . . Laatsch, H. (2005). Chinikomycins A and B: isolation, structure elucidation, and biological activity of novel antibiotics from a marine Streptomyces sp. isolate M045. *J Nat Prod, 68*(3), 349-353. doi:10.1021/np030518r

93. Li, X., Tambong, J., Yuan, K. X., Chen, W., Xu, H., Levesque, C. A., & De Boer, S. H. (2018). Re-classification of Clavibacter michiganensis subspecies on the basis of whole-genome and multi-locus sequence analyses. *Int J Syst Evol Microbiol, 68*(1), 234-240. doi:10.1099/ijsem.0.002492

94. Liu, S.W., Zhai, X.X., Liu, D., Liu, Y.Y., Sui, L.Y., Luo, K.K., Yang, Q., Li, F.N., Nikandrova, A.A., Imamutdinova, A.N. and Lukianov, D.A., (2023). Bioprospecting of Actinobacterial Diversity and Antibacterial Secondary Metabolites from the Sediments of Four Saline Lakes on the Northern Tibetan Plateau. Microorganisms, 11(10), 2475.

95. Lloret, A., Hartmann, K., Pennisi, M. G., Gruffydd-Jones, T., Addie, D., Belak, S., . . . Horzinek, M. C. (2013). Mycobacterioses in cats: ABCD guidelines on prevention and management. *J Feline Med Surg, 15*(7), 591-597. doi:10.1177/1098612X13489221

96. Ludwig, W., Euzéby, J., Schumann, P., Busse, H.-J., Trujillo, M. E., Kämpfer, P., & Whitman, W. B. (2012). Road map of the phylum Actinobacteria. *Bergey's Manual of Systematic Bacteriology*.

97. Mahajan GB, Balachandran L. Antibacterial agents from actinomycetes - a review. Front Biosci (Elite Ed). 2012 Jan 1;4:240-53. doi: 10.2741/373. PMID: 22201868.

98. Manam, R. R., Teisan, S., White, D. J., Nicholson, B., Grodberg, J., Neuteboom, S. T., . . . Potts, B. C. (2005). Lajollamycin, a nitro-tetraene spiro-beta-lactone-gamma-lactam antibiotic from the marine actinomycete Streptomyces nodosus. *J Nat Prod, 68*(2), 240-243. doi:10.1021/np049725x

99. Manikkam, R., Thenmozhli, G.S., Ranjani, S., Kishore Kumar, A., Azhagesan, S., Manigundan, K., Gopikrishnan, V., Parthasarathy, K., Shanmugasundaram, T., Sasirekha, S. and Balagurunathan, R., (2024). Translational Research in Microbial Healthcare Products with Special Reference to Anticancer Drug Discovery from Actinobacteria. In Translational Research in Biomedical Sciences: Recent Progress and Future Prospects (pp. 145-165). Singapore: Springer Nature Singapore.

100. Manivasagan, P., Venkatesan, J., Sivakumar, K., & Kim, S. K. (2016). Actinobacteria mediated synthesis of nanoparticles and their biological properties: A review. *Crit Rev Microbiol, 42*(2), 209-221. doi:10.3109/1040841X.2014.917069

101. Marchand, G., Wingert, L., Viegas, C., Caetano, L., Viegas, S., Twaruzek, M., Lacombe, N., Lanoie, D., Valois, I., Gouin, F. and Soszczyńska, E., (2024). Assessment of waste workers occupational risk to microbial agents and cytotoxic effects of mixed contaminants present in the air of waste truck cabin and ventilation filters. Journal of the Air & Waste Management Association, 74(3), 145-162.

102. Marchant, R., & Banat, I. M. (2012). Microbial biosurfactants: challenges and opportunities for future exploitation. *Trends Biotechnol, 30*(11), 558-565. doi:10.1016/j.tibtech.2012.07.003

103. McCarthy, A. J., & Williams, S. T. (1990). Methods for Studying the Ecology of Actinomycetes. *Methods In Microbiology*.

104. Menendez, N., Nur-e-Alam, M., Brana, A. F., Rohr, J., Salas, J. A., & Mendez, C. (2004). Biosynthesis of the antitumor chromomycin A3 in Streptomyces griseus: analysis of the gene cluster and rational design of novel chromomycin analogs. *Chem Biol, 11*(1), 21-32. doi:10.1016/j.chembiol.2003.12.011

105. Motallebirad, T., Tashakor, A., Abniki, R., & Azadi, D. (2023). 15 years of phenotypic and genotypic surveillance and antibiotic susceptibility pattern of actinomycetes (Mycobacterium, Nocardia, Rhodococcus, etc.) in clinical and environmental samples of Iran. Diagnostic Microbiology and Infectious Disease, 116080.

106. Mukhopadhyay, R., & Biswas, K. (2024). Reports of Actinomycetes to Degrade Microplastic. In Microplastic Pollution (pp. 473-489). Singapore: Springer Nature Singapore.

107. Murray, K., Rogers, R., Selvey, L. A., Selleck, P., Hyatt, A., Gould, A....Westbury, H. (1995). A Novel Morbillivirus Pneumonia of Horses and its Transmission to Humans. *Emerging Infectious Diseases*, *1*(1), 31-33. https://doi.org/10.3201/eid0101.950107.

108. Nakajima, M., Itoi, K., Takamatsu, Y., Kinoshita, T., Okazaki, T., Kawakubo, K., . . . Haneishi, T. (1991). Hydantocidin: a new compound with herbicidal activity from Streptomyces hygroscopicus. *J Antibiot (Tokyo), 44*(3), 293-300. doi:10.7164/antibiotics.44.293

109. Nandi, M., Macdonald, J., Liu, P., Weselowski, B., & Yuan, Z. C. (2018). Clavibacter michiganensis ssp. michiganensis: bacterial canker of tomato, molecular interactions and disease management. *Mol Plant Pathol*. doi:10.1111/mpp.12678

110. Nascimento, F. X., Rossi, M. J., Soares, C. R., McConkey, B. J., & Glick, B. R. (2014). New insights into 1-aminocyclopropane-1-carboxylate (ACC) deaminase phylogeny, evolution and ecological significance. *PLoS One, 9*(6), e99168. doi:10.1371/journal.pone.0099168

111. Nicolaou, K. C., Becker, J., Lim, Y. H., Lemire, A., Neubauer, T., & Montero, A. (2009). Total synthesis and biological evaluation of (+)- and (-)-bisanthraquinone antibiotic BE-43472B and related compounds. *J Am Chem Soc, 131*(41), 14812-14826. doi:10.1021/ja9073694

112. Noordeen, S. K. (1994). Elimination of leprosy as a public health problem. *Indian J Lepr, 66*(1), 1-10. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/7983387

113. Oh, D. C., Gontang, E. A., Kauffman, C. A., Jensen, P. R., & Fenical, W. (2008). Salinipyrones and pacificanones, mixed-precursor polyketides from the marine actinomycete Salinispora pacifica. *J Nat Prod, 71*(4), 570-575. doi:10.1021/np0705155

114. Olano, C., Mendez, C., & Salas, J. A. (2009). Antitumor compounds from marine actinomycetes. *Mar Drugs, 7*(2), 210-248. doi:10.3390/md7020210

115. Omura, S., Takahashi, Y., Iwai, Y., & Tanaka, H. (1982). Kitasatosporia, a new genus of the order Actinomycetales. *J Antibiot (Tokyo), 35*(8), 1013-1019. doi:10.7164/antibiotics.35.1013

116. Osdaghi, E., Young, A. J., & Harveson, R. M. (2020). Bacterial wilt of dry beans caused by Curtobacterium flaccumfaciens pv. flaccumfaciens: A new threat from an old enemy. *Mol Plant Pathol, 21*(5), 605-621. doi:10.1111/mpp.12926

117. Paananen, A., Mikkola, R., Sareneva, T., Matikainen, S., Andersson, M., Julkunen, I., . . . Timonen, T. (2000). Inhibition of human NK cell function by valinomycin, a toxin from Streptomyces griseus in indoor air. *Infect Immun, 68*(1), 165-169. doi:10.1128/iai.68.1.165-169.2000

118. Palaniappan, N., Ayers, S., Gupta, S., Habib el, S., & Reynolds, K. A. (2006). Production of hygromycin A analogs in Streptomyces hygroscopicus NRRL 2388 through identification and manipulation of the biosynthetic gene cluster. *Chem Biol, 13*(7), 753-764. doi:10.1016/j.chembiol.2006.05.013

119. Pandey, A., Nigam, P., Soccol, C. R., Soccol, V. T., Singh, D., & Mohan, R. (2000). Advances in microbial amylases. *Biotechnol Appl Biochem, 31*(2), 135-152. doi:10.1042/ba19990073

120. Park, J., Lee, P. A., Lee, H. H., Choi, K., Lee, S. W., & Seo, Y. S. (2017). Comparative Genome Analysis of Rathayibacter tritici NCPPB 1953 with Rathayibacter toxicus Strains Can Facilitate Studies on Mechanisms of Nematode Association and Host Infection. *Plant Pathol J, 33*(4), 370-381. doi:10.5423/PPJ.OA.01.2017.0017

121. Parras-Moltó M, Lund D, Ebmeyer S, Larsson DGJ, Johnning A & Kristiansson E. (2025) The transfer of antibiotic resistance genes between evolutionarily distant bacteria. mSphere. 10(6):e0011425.

122. Petkovic, H., Lukezic, T., & Suskovic, J. (2017). Biosynthesis of Oxytetracycline by Streptomyces rimosus:Past, Present and Future Directions in the Developmentof Tetracycline Antibiotics. *Food Technol Biotechnol, 55*(1), 3-13. doi:10.17113/ftb.55.01.17.4617

123. Pine, L., Malcolm, G. B., Curtis, E. M., & Brown, J. M. (1981). Demonstration of Actinomyces and

Arachnia species in cervicovaginal smears by direct staining with species-specific fluorescent-antibody conjugate. *J Clin Microbiol, 13*(1), 15-21. doi:10.1128/JCM.13.1.15-21.1981

124. Pinoy, E. (1913). Actinomycoses et mycétomes. *Bull. Inst. Pasteur*, *11*, 929-976.

125. Polti MA, Aparicio JD, Benimeli CS, Amoroso MJ. Role of Actinobacteria in bioremediation. In: Das S, editor. *Microbial biodegradation and bioremediation.* New York, NY: Elsevier; 2014. pp. 269–286.

126. Pongen, Y. L., Thirumurugan, D., Ramasubburayan, R., & Prakash, S. (2023). Harnessing actinobacteria potential for cancer prevention and treatment. Microbial Pathogenesis, 183, 106324.

127. Prakash, D., Nawani, N., Prakash, M., Bodas, M., Mandal, A., Khetmalas, M., & Kapadnis, B. (2013). Actinomycetes: a repertory of green catalysts with a potential revenue resource. *Biomed Res Int, 2013*, 264020. doi:10.1155/2013/264020

128. Qi, D., Zou, L., Zhou, D., Chen, Y., Gao, Z., Feng, R., . . . Wang, W. (2019). Taxonomy and Broad-Spectrum Antifungal Activity of Streptomyces sp. SCA3-4 Isolated From Rhizosphere Soil of Opuntia stricta. *Front Microbiol, 10*, 1390. doi:10.3389/fmicb.2019.01390

129. Qin, S., Li, W. J., Dastager, S. G., & Hozzein, W. N. (2016). Editorial: Actinobacteria in Special and Extreme Habitats: Diversity, Function Roles, and Environmental Adaptations. *Front Microbiol, 7*, 1415. doi:10.3389/fmicb.2016.01415

130. Quinn, G. A., & Dyson, P. J. (2024). Going to extremes: progress in exploring new environments for novel antibiotics. npj Antimicrobials and Resistance, 2(1), 8.

131. Ramezani-Moghadam, M., Baghaee-Ravari, S., & Taghavi, M. (2024). Studying the pathogenic Streptomyces strains responsible for causing potato common scab in Iran and assessing the efficacy of native S. fimicarius-ghR and S. rochei-FsG in reducing scab lesion development in both potato and radish hosts in vivo. Biocontrol Science and Technology, 1-28.

132. Ranjani, A., Gopinath, P. M., Rajesh, K., Dhanasekaran, D., & Priyadharsini, P. (2016). Diversity of Silver Nanoparticle Synthesizing Actinobacteria Isolated from Marine Soil, Tamil Nadu, India. *Arabian Journal for Science and Engineering volume*.

133. Rathore DS, Sheikh M, Singh SP. Marine Actinobacteria: new horizons in bioremediation. In: Prasad R, Kumar V, Singh J, Upadhyaya CP, editors. *Recent developments in microbial technologies.* Singapore: Springer; 2021. pp. 425–449.

134. Ravikumar, S., Gnanadesigan, M., Saravanan, A., Monisha, N., Brindha, V., & Muthumari, S. (2012). Antagonistic properties of seagrass associated Streptomyces sp. RAUACT-1: a source for anthraquinone rich compound. *Asian Pac J Trop Med, 5*(11), 887-890. doi:10.1016/S1995-7645(12)60165-5

135. Reller, L. B., Maddoux, G. L., Eckman, M. R., & Pappas, G. (1975). Bacterial endocarditis caused by Oerskovia turbata. *Ann Intern Med, 83*(5), 664-666. doi:10.7326/0003-4819-83-5-664

136. Ribeiro, I., Antunes, J.T., Alexandrino, D.A., Tomasino, M.P., Almeida, E., Hilário, A., Urbatzka, R., Leão, P.N., Mucha, A.P. and Carvalho, M.F., (2023). Actinobacteria from Arctic and Atlantic deep-sea sediments—Biodiversity and bioactive potential. Frontiers in Microbiology, 14, 1158441.

137. Rokas, A., Williams, B. L., King, N., & Carroll, S. B. (2003). Genome-scale approaches to resolving incongruence in molecular phylogenies. *Nature*, *425*(6960), 798-804.

138. Rzewuska, M., Kwiecien, E., Chrobak-Chmiel, D., Kizerwetter-Swida, M., Stefanska, I., & Gierynska, M. (2019). Pathogenicity and Virulence of Trueperella pyogenes: A Review. *Int J Mol Sci, 20*(11). doi:10.3390/ijms20112737

139. S.T.Williams, M.Shameemullah, & E.T.WatsonC.I.Mayfield. (2002). Studies on the ecology of actinomycetes in soil—VI. The influence of moisture tension on growth and survival.

140. Saha, S., Dhanasekaran, D., Shanmugapriya, S., & Latha, S. (2013). Nocardiopsis sp. SD5: a potent feather degrading rare actinobacterium isolated from feather waste in Tamil Nadu, India. *J Basic Microbiol, 53*(7), 608-616. doi:10.1002/jobm.201200105

141. Sayed A., Hassan M., Alhadrami H., Hassan H., Goodfellow M., Rateb M. (2020). Extreme environments: microbiology leading to specialized metabolites. *J. Appl. Microbiol.* 128 630–657. 10.1111/jam.14386

142. Schmidt, A., Haferburg, G., Sineriz, M., Merten, D., Büchel, G., & Kothe, E. (2005). Heavy metal resistance mechanisms in actinobacteria for survival in AMD contaminated soils. *Geochemistry*, *65*, 131–144. https://doi.org/10.1016/j.chemer.2005.06.006

143. Sekurova, O. N., Zhang, J., Kristiansen, K. A., & Zotchev, S. B. (2016). Activation of chloramphenicol biosynthesis in Streptomyces venezuelae ATCC 10712 by ethanol shock: insights from the promoter fusion studies. *Microb Cell Fact, 15*, 85. doi:10.1186/s12934-016-0484-9

144. Selim M., Abdelhamid S. A., Mohamed S. S. (2021). Secondary metabolites and biodiversity of actinomycetes. *J. Genet. Eng. Biotechnol.* 19:1. 10.1186/s43141-021-00156-9

145. Setiawan, E., Hermanto, M. E., Abdulgani, N., Prasetyo, E. N., Riani, C., Wulandari, D., & Budiharjo, A. (2024). A Mini Review on Analysis of Potential Antibacterial Activity of Symbiotic Bacteria from Indonesian Freshwater Sponge: An Unexplored and A Hidden Potency. Journal of Tropical Biodiversity and Biotechnology, 9(1), 82682.

146. Sharmin, T., Rahman, M. A., Anisuzzaman, A. S. M., & Islam, M. A.-U. (2013). Antimicrobial and Cytotoxic Activities of Secondary Metabolites Obtained from a Novel Species of Streptomyces. *Bangladesh Pharmaceutical Journal*

147. Sheldon, P. J., Mao, Y., He, M., & Sherman, D. H. (1999). Mitomycin resistance in Streptomyces lavendulae includes a novel drug-binding-protein-dependent export system. *J Bacteriol, 181*(8), 2507-2512. doi:10.1128/JB.181.8.2507-2512.1999

148. Shen, J., Kong, L., Li, Y., Zheng, X., Wang, Q., Yang, W., . . . You, D. (2019). A LuxR family transcriptional regulator AniF promotes the production of anisomycin and its derivatives in Streptomyces hygrospinosus var. beijingensis. *Synth Syst Biotechnol, 4*(1), 40-48. doi:10.1016/j.synbio.2018.12.004

149. Shi, W., Li, M., Wei, G., Tian, R., Li, C., Wang, B., . . . Gao, Z. (2019). The occurrence of potato common scab correlates with the community composition and function of the geocaulosphere soil microbiome. *Microbiome, 7*(1), 14. doi:10.1186/s40168-019-0629-2

150. Shivlata, L., & Satyanarayana, T. (2015). Thermophilic and alkaliphilic Actinobacteria: biology and potential applications. *Front Microbiol, 6*, 1014. doi:10.3389/fmicb.2015.01014

151. Singh, R., & Dubey, A. K. (2018). Diversity and Applications of Endophytic Actinobacteria of Plants in Special and Other Ecological Niches. *Front Microbiol, 9*, 1767. doi:10.3389/fmicb.2018.01767

152. Smith, I. (2003). Mycobacterium tuberculosis pathogenesis and molecular determinants of virulence. *Clin Microbiol Rev, 16*(3), 463-496. doi:10.1128/cmr.16.3.463-496.2003

153. Snel, B., Huynen, M. A., & Dutilh, B. E. (2005). Genome trees and the nature of genome evolution. *Annu Rev Microbiol, 59*, 191-209. doi:10.1146/annurev.micro.59.030804.121233

154. Soler, A., Garcia-Hernandez, J., Zornoza, A., & Alonso, J. L. (2018). Diversity of culturable nocardioform actinomycetes from wastewater treatment plants in Spain and their role in the biodegradability of aromatic compounds. *Environ Technol, 39*(2), 172-181. doi:10.1080/09593330.2017.1296897

155. Solomon D., et al.. (2020). Epidemiology and Risk Factors of Pyelonephritis in Israeli Dairy Cattle. Israel Journal of Veterinary Medicine Vol. 75 (1)

156. Stes, E., Francis, I., Pertry, I., Dolzblasz, A., Depuydt, S., & Vereecke, D. (2013). The leafy gall syndrome induced by Rhodococcus fascians. *FEMS Microbiol Lett, 342*(2), 187-194. doi:10.1111/1574-6968.12119

157. Świecimska, M., Golińska, P., & Goodfellow, M. (2023). Generation of a high quality library of bioactive filamentous actinomycetes from extreme biomes using a culture-based bioprospecting strategy. Frontiers in Microbiology, 13, 1054384.

158. Takeuchi, M., & Hatano, K. (1998). Union of the genera Microbacterium Orla-Jensen and Aureobacterium Collins et al. in a redefined genus Microbacterium. *Int J Syst Bacteriol, 48 Pt 3*, 739-747. doi:10.1099/00207713-48-3-739

159. Tan, H., Deng, Z., & Cao, L. (2009). Isolation and characterization of actinomycetes from healthy goat faeces. *Lett Appl Microbiol, 49*(2), 248-253. doi:10.1111/j.1472-765X.2009.02649.x

160. Tanaka, Y., & Omura, S. (1993). Agroactive compounds of microbial origin. *Annu Rev Microbiol, 47*, 57-87. doi:10.1146/annurev.mi.47.100193.000421

161. Tischler, D., van Berkel, W. J. H., & Fraaije, M. W. (2019). Editorial: Actinobacteria, a Source of Biocatalytic Tools. *Front Microbiol, 10*, 800. doi:10.3389/fmicb.2019.00800

162. Turroni, F., Peano, C., Pass, D. A., Foroni, E., Severgnini, M., Claesson, M. J., . . . Ventura, M. (2012). Diversity of bifidobacteria within the infant gut microbiota. *PLoS One, 7*(5), e36957. doi:10.1371/journal.pone.0036957

163. Umezawa, H., Hamada, M., Suhara, Y., Hashimoto, T., & Ikekawa, T. (1965). Kasugamycin, a new antibiotic. *Antimicrob Agents Chemother (Bethesda), 5*, 753-757. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/5883494

164. Van Bergeijk, D. A., Terlouw, B. R., Medema, M. H., & van Wezel, G. P. (2020). Ecology and genomics of Actinobacteria: new concepts for natural product discovery. Nature Reviews Microbiology, 18(10), 546-558.

165. Ventura, M., Canchaya, C., Fitzgerald, G. F., Gupta, R. S., & van Sinderen, D. (2007). Genomics as a means to understand bacterial phylogeny and ecological adaptation: the case of bifidobacteria.

Antonie Van Leeuwenhoek, 91(4), 351-372. doi:10.1007/s10482-006-9122-6

166. Verma, M., Lal, D., Kaur, J., Saxena, A., Kaur, J., Anand, S., & Lal, R. (2013). Phylogenetic analyses of phylum Actinobacteria based on whole genome sequences. *Res Microbiol, 164*(7), 718-728. doi:10.1016/j.resmic.2013.04.002

167. Waksman, S. A. (1953). Streptomycin: background, isolation, properties, and utilization. *Science, 118*(3062), 259-266. doi:10.1126/science.118.3062.259

168. Wehlburg, C. (1966). BACTERIAL LEAF SPOT OF POINSETTIA. In Florida Department of Agriculture & Division of Plant Industry, *Plant Pathology Circular No. 52*. https://ccmedia.fdacs.gov/content/download/11058/file/pp52.pdf

169. Wellington, E. M., Stackebrandt, E., Sanders, D., Wolstrup, J., & Jorgensen, N. O. (1992). Taxonomic status of Kitasatosporia, and proposed unification with Streptomyces on the basis of phenotypic and 16S rRNA analysis and emendation of Streptomyces Waksman and Henrici 1943, 339AL. *Int J Syst Bacteriol, 42*(1), 156-160. doi:10.1099/00207713-42-1-156

170. Wilson, J. W. (2012). Nocardiosis: updates and clinical overview. *Mayo Clin Proc, 87*(4), 403-407. doi:10.1016/j.mayocp.2011.11.016

171. Wilson, M. C., Gulder, T. A., Mahmud, T., & Moore, B. S. (2010). Shared biosynthesis of the saliniketals and rifamycins in Salinispora arenicola is controlled by the sare1259-encoded cytochrome P450. *J Am Chem Soc, 132*(36), 12757-12765. doi:10.1021/ja105891a

172. Wu, S. J., Fotso, S., Li, F., Qin, S., Kelter, G., Fiebig, H. H., & Laatsch, H. (2006). N-carboxamido-staurosporine and selina-4(14),7(11)-diene-8,9-diol, new metabolites from a marine Streptomyces sp. *J Antibiot (Tokyo), 59*(6), 331-337. doi:10.1038/ja.2006.46

173. Xiliang, J. (1994). The mechanism of agricultural antibiotic.

174. Yadav, A.N., Verma, P., Kumar, S., Kumar, V., Kumar, M., Sugitha, T.C.K., Singh, B.P., Saxena, A.K. and Dhaliwal, H.S., (2018). Actinobacteria from rhizosphere: molecular diversity, distributions, and potential biotechnological applications. In New and future developments in microbial biotechnology and bioengineering (pp. 13-41). Elsevier.

175. Yang S, Zhang W, Yang B, Feng X, Li Y, Li X and Liu Q (2024) Metagenomic evidence for antibiotic-associated actinomycetes in the Karamay Gobi region. Front. Microbiol. 15:1330880.

176. Zenova, G. M., Manucharova, N. A., & Zvyagintsev, D. G. (2011). Extremophilic and extremotolerant actinomycetes in different soil types.

177. Zhang, Z., Wang, Y., & Ruan, J. (1997). A proposal to revive the genus Kitasatospora (Omura, Takahashi, Iwai, and Tanaka 1982). *Int J Syst Bacteriol, 47*(4), 1048-1054. doi:10.1099/00207713-47-4-1048

178. Zhi, X. Y., Li, W. J., & Stackebrandt, E. (2009). An update of the structure and 16S rRNA gene sequence-based definition of higher ranks of the class Actinobacteria, with the proposal of two new suborders and four new families and emended descriptions of the existing higher taxa. *Int J Syst Evol Microbiol, 59*(Pt 3), 589-608. doi:10.1099/ijs.0.65780-0