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Biological Control Using Actinobacteria against Plant Pathogens, Its Mechanisms and Secondary Metabolites. A Review

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Abstract

Actinobacteria have become major players in the field of biological control, which is an eco-friendly method of controlling plant diseases. A vast range of secondary metabolites with antibacterial properties are produced by these gram-positive bacteria, which are well known for their varied metabolic capabilities. Actinobacteria can successfully inhibit the growth of harmful plant pathogens through a variety of methods, including competition for resources, antibiotic synthesis, and stimulation of plant defensive responses. In addition to advancing our understanding of microbial ecology, an understanding of these interactions leads the way for the development of sustainable farming methods that reduce the need for chemical pesticides, therefore encouraging healthier ecosystems and increasing crop yields. This innovative approach highlights the value of actinobacteria and their function in managing plant diseases. It also shows how these natural processes can be used in biocontrol strategies, opening the door to sustainable solutions that have the potential to modify agricultural practices around the world. In addition to improving our understanding of actinobacteria's function in soil health, knowing the precise mechanisms of action they use helps design focused biocontrol strategies that can effectively target plant pathogens while reducing the need for chemical solutions. Sustainable farming methods that put ecological balance first and encourage long-term soil fertility are what this strategy aims to promote. Here, we provide an overview of using actinobacteria as a biological control against various plant pathogens and its important secondary metabolites.

Keywords: Actinobacteria - Secondary metabolites - Biological control - Sustainable farming

INTRODUCTION

The increasing need for food production worldwide calls for methods to reduce agricultural losses driven on by plant diseases. Despite their effectiveness, synthetic pesticides present significant hazards to human health and the environment (Kaur et al., 2023; Da Cruz Silva et al., 2022). As a result, interest in sustainable alternatives is rising, and one promising strategy is biological control through the use of beneficial microbes (Ebrahimi-Zarandi et al., 2022; Ribeiro & Van Der Sand, 2024). The potential of actinobacteria, a diverse phylum of Gram-positive bacteria, as biocontrol agents against a variety of plant pathogens has attracted a lot of attention (Diab et al., 2024; Belt et al., 2021; Gowdar et al., 2018). This paper explores the variety of secondary metabolite synthesis processes used by actinobacteria in biological regulation. It’s interesting to note that actinobacteria support plant growth in addition to suppressing infections. Actinobacteria are useful tools for sustainable agriculture because of their dual function of suppressing pathogens and promoting growth (Palaniyandi et al., 2013). Furthermore, Actinobacteria produce antibiotics, lytic enzymes, siderophores, and induce systemic resistance in plants as ways of suppressing disease (Bouizgarne, 2012; Ebrahimi-Zarandi et al., 2022). Through a variety of ways, actinomycetes, especially those of the Streptomyces genus, show great promise as biocontrol agents against plant diseases. These microbes are recognized for being able for producing a broad range of extracellular enzymes and antibiotics, which makes them powerful biocontrol agents (Doumbou et al., 2005). It's interesting to note that actinomycetes have many biological regulatory systems besides the synthesis of enzymes. Numerous antibiotics and other bioactive compounds that may effectively control bacterial and fungal plant diseases are known to be produced by them (Doumbou et al., 2005; Silva et al., 2022). Furthermore, actinomycetes have the ability to promote plant growth, which enhances plant health and resistance to disease (Chaurasia et al., 2018; Doumbou et al., 2005). Beyond that, plant-derived endophytic actinobacteria have demonstrated encouraging outcomes in managing a range of phytopathogens. It has been demonstrated that endophytic Streptomycetes' power to suppress phytopathogenic fungus is strongly linked to their chitinase enzyme production (Quecine et al., 2008). This genetic association offers a better knowledge of endophytic Streptomyces as a biocontrol agent by indicating that the biocontrol activity may take place inside the host plant. In pepper fruits and plants, for example, *Streptomyces griseocarneus* R132, which was isolated from *Paullinia cupana*, showed substantial suppression of several plant pathogens and successfully managed anthracnose induced by *Colletotrichum gloeosporioides* (Liotti et al., 2019). Furthermore, according to Liotti et al. (2019), *Streptomyces griseocarneus* R132 enhanced the pepper plants' shoot dry mass by 42%. It's interesting to note that although actinobacteria are mostly recognized for their advantageous functions in plant health, several species are also capable of acting as plant diseases (Barka et al., 2015). The complicated interactions between actinobacteria and plants are highlighted by their dual nature. However, actinobacteria-based strategies for integrated plant disease management and sustainable agriculture have been developed as a result of the focus on their biocontrol capabilities (Doumbou et al., 2005; Ebrahimi-Zarandi et al., 2022).

1. Mechanisms of Actinobacterial Biocontrol

Actinobacteria use a variety of complex mechanisms, frequently working in concert, to achieve their biocontrol effects. These processes come into two general categories: direct and indirect.

1.1. Direct Mechanisms

Direct mechanisms entail the plant pathogen being directly inhibited or killed. The following direct mechanisms are highlighted by several studies:

1.1.1. Antibiosis:

The most well researched direct method is probably antibiosis, which involves actinobacteria producing and releasing a variety of antimicrobial substances. These substances, which are frequently secondary metabolites, prevent plant pathogens from growing, developing, or surviving (Ribeiro & Van Der Sand, 2024; Belt et al., 2021; Gowdar et al., 2018). The biggest genus of Actinobacteria, Streptomyces, is especially well-known for producing a significant number of these substances (Gowdar et al., 2018; Belt et al., 2021; Khan et al., 2023). These consist of bioactive compounds such as antibiotics and antifungal substances (Diab et al., 2024; Liotti et al., 2019; Renuka et al., 2023). Depending on the actinobacterial strain and the surrounding circumstances, various compounds are produced (Cordovez et al., 2015; Gómez et al., 2021; Dow et al., 2023). Actinomycetes use antibiosis, a crucial biological control mechanism, to combat a variety of plant diseases. This subject matter is covered in a number of works in the context given: According to Liotti et al. (2019), *Streptomyces griseocarneus* R132, an endophytic actinobacterium that was isolated from *Paullinia cupana*, showed potent antibiosis against a variety of phytopathogens, preventing their growth by as much as 73.93%. This strain demonstrated the potential of actinomycetes in pre- and post-harvest disease control through antibiosis by successfully controlling anthracnose in pepper fruits and plants. It's interesting to note that, despite being an essential process, antibiosis frequently functions in tandem with other biological control techniques. Some methods, for example, combine antibiosis with pathogen cell wall enzyme breakdown or host plant resistance induction (Elad, 1996). This multifaceted strategy increases biological control agents' efficacy. The distinct metabolic pathways of marine actinomycetes, which generate a range of bioactive compounds with cytotoxic, antibacterial, and antiviral properties, make them especially remarkable (Yang et al., 2020).

1.1.2. Parasitism:

Actinobacteria exhibit significant potential in suppressing plant pathogens through multiple mechanisms, which includes parasitism. Numerous bioactive compounds and enzymes produced by these bacteria, which are abundantly found in soil and plant tissues, have the ability to effectively fight plant diseases (Hazarika & Thakur, 2020; Li et al., 2011). Actinobacteria are more efficient in controlling pathogens because they can penetrate plant tissues as endophytes (Singh & Dubey, 2018). According to Kaur et al. (2023), certain actinobacteria have the ability to directly attack and colonize fungal hyphae. The pathogen dies or functioning less well as a result of the lytic enzymes that degrade the fungal cell wall (Gowdar et al., 2018; Renuka et al., 2023; Alblooshi et al., 2021). One important component of fungal cell walls, chitin, can be attacked by chitinases (Wang et al., 2021; Ruangwong et al., 2022; Alblooshi et al., 2021). Another important component of fungal cell walls, β-1,3-glucan, is broken down by β-1,3-glucanases (Wang et al., 2021; Ruangwong et al., 2022). The ability of some actinobacterial strains to function as biocontrol agents depends on their ability to produce these enzymes (Abo-Zaid et al., 2024; Hamad et al., 2021; Ruangwong et al., 2022).

1.1.3. Competition for nutrients and space:

Actinobacteria, a diverse group of Gram-positive bacteria, play major roles in plant-associated microbe communities, including as symbionts and competitors against plant pathogens (Barka et al., 2015). These bacteria are potential sources of new compounds for agricultural uses because they are prevalent in soil and have evolved to a variety of biological environments (Singh & Dubey, 2018). Actinobacteria can indirectly increase plant development by decreasing disease levels through competition for nutrients and space (Lugtenberg & Kamilova, 2009). In environments such the rhizosphere where nutrients are scarce, this competition is especially significant. It is well known that actinobacteria, particularly those from genera like Streptomyces, create a variety of secondary metabolites, such as antibiotics and antifungal substances, that can stop plant pathogens from growing (Barka et al., 2015; Hazarika & Thakur, 2020). Also, some actinobacteria produce siderophores, which are iron-chelating molecules that can sequester iron from the environment in conditions of nutrient competition. The growth of harmful microbes that need iron for metabolism may be inhibited by this iron sequestration (Stubbendieck et al., 2019). Plant pathogens and actinobacteria compete for essential resources including nutrients and rhizosphere space (Gowdar et al., 2018; Kaur et al., 2023). The pathogen's ability to spread and cause disease may be reduced by this competitive exclusion. Actinobacteria prevent the pathogen from obtaining this vital nutrient by binding iron more efficiently than the pathogen, which inhibits the disease's ability to develop and spread (Gowdar et al., 2018), (Kamil, 2018).

1.2. Indirect Mechanisms

By activating plant defense mechanisms, indirect mechanisms increase a plant's resistance to pathogen attack. The synthesis of signaling molecules or the activation of genes linked to plant defense frequently mediate these processes:

1.2.1. Induced Systemic Resistance (ISR):

Actinobacteria have significance for inducing plants to develop systemic resistance to infections. Systemic resistance against infections can be induced by non-pathogenic actinobacteria, although its specific mechanisms are still unknown.Actinobacteria trigger a moderate defense response in plants when pathogens are not present. This response involves pathogenesis-related proteins and secondary plant metabolites and is triggered by jasmonic acid and salicylic acid signaling (Ebrahimi-Zarandi et al., 2022). With the added participation of ethylene signaling revealed, this priming response partially consists of the same compounds as the response to a single actinobacterium (Ebrahimi-Zarandi et al., 2022; Ent et al., 2009). Remarkably, some rhizobacteria may activate distinct signaling pathways that are not dependent on salicylic acid, such as those that rely on ethylene and jasmonic acid signaling, but others can activate the salicylic acid-dependent systemic acquired resistance (SAR) pathway (Rabari et al., 2022). According to Ebrahimi-Zarandi et al. (2022) and Conn et al. (2008), actinobacteria have the ability to cause systemic resistance in plants, which triggers the plant's defenses against a wide range of diseases. Signaling pathways related to ethylene, salicylic acid, and jasmonic acid are frequently activated during this priming (Ebrahimi-Zarandi et al., 2022; Belt et al., 2021; Conn et al., 2008). For example, it has been demonstrated that Streptomyces rochei ACTA1551 uses ISR to protect tomato seeds from Fusarium oxysporum infection (Kanini et al., 2013). Depending on the plant species and the actinobacterial strain, different genes have been associated in ISR (Conn et al., 2008).

1.2.2. Plant Growth Promotion:

In addition to producing pest-antagonistic secondary metabolites and enzymes, these helpful microbes, which make up a significant percentage of rhizosphere communities and colonize plant tissues, also promote plant growth (Ebrahimi-Zarandi et al., 2022). Nitrogen fixation, phosphate solubilization, and the synthesis of phytohormones like indole-3-acetic acid (IAA) are among the many plants growth-promoting (PGP) characteristics displayed by actinobacteria (Da Cruz Silva et al., 2022; Gowdar et al., 2018; Wang et al., 2021; Saikia et al., 2022). By improving plant vigor and general health, these PGP features can indirectly increase a plant's resistance to pathogen attacks (Da Cruz Silva et al., 2022; Gowdar et al., 2018; Wang et al., 2021). *Streptomyces griseocarneus* R132, for example, increases shoot dry mass by 42%, which encourages plant growth (Liotti et al., 2019). Likewise, *Streptomyces djakartensis* MEPS155 has PGP characteristics, such as IAA synthesis and the ability to fix nitrogen and solubilize phosphorus (Zhang et al., 2024).

2. Secondary Metabolites and its Role in Biocontrol

Actinomycetes are useful biocontrol agents because of the secondary metabolites they produce, which are essential to their antibiosis mechanism against plant infections. The significance of these metabolites in protecting and promoting plant growth has been emphasized by numerous research. Numerous bioactive secondary metabolites with antibacterial qualities are produced by actinomycetes, especially those recovered from the rhizosphere (Elshafie et al., 2023; Solecka et al., 2012). These substances show efficacy against a range of phytopathogens, including as fungus and bacteria. In vitro, for example, actinomycetes isolates' cell-free culture filtrates shown antibacterial efficacy against common plant diseases (Elshafie et al., 2023). Twenty distinct components, including N-Acetyl-l-histidinol, Rhizocticin A, and Eponemycin, were identified by chemical analysis of these metabolites. These components could be utilized to create innovative bio-formulations for crop protection (Elshafie et al., 2023). Remarkably, actinomycetes' secondary metabolites promote induced systemic resistance (ISR) in plants in addition to directly inhibiting pathogen growth (Borriss et al., 2019). Actinomycetes' total efficiency as biocontrol agents is increased by this dual approach. Furthermore, certain biocontrol strains create volatile organic compounds (VOCs) that enhance their antibacterial activity, indicating a complex interaction between different metabolites in the biocontrol function (Borriss et al., 2019). The effectiveness of actinobacteria as biocontrol agents is largely dependent on the variety of secondary metabolites they produce. Numerous biological actions, such as antibacterial, antifungal, and growth-promoting properties, can be observed by these metabolites. The actinobacterial strain, growth circumstances, and the presence of other microorganisms all have a significant impact on the particular metabolites that are generated (Dinesh et al., 2017; Alwali & Parkinson, 2023).

2.1. Various Chemical Forms

2.1.1. Antibiotics produced by actinobacteria that involved in antibiosis against plant pathogens (Non-volatile Antibiotics):

Actinobacteria are noted producers of non-volatile antibiotics, numerous of which have been used in human and veterinary medicine (Selim, 2021), (Meij, 2017). These antibiotics target multiple biological processes in pathogens, leading to growth inhibition or cell death (Selim, 2021), (Meij, 2017). Examples of antibiotics generated by actinobacteria include chloramphenicol, granaticin, and althiomycin. (Liu, 2022). A diverse array of antibiotics with antibiosis against different plant diseases are known to be produced by actinobacteria. The antibacterial properties of actinobacteria that were isolated from the rhizosphere of medicinal plants are highlighted by Zhao et al. (2012). All Streptomyces isolates had antibacterial action, according to the study, and a few uncommon actinobacteria stopped the growth of plant diseases such *Fusarium oxysporum* and *Verticillium dahliae* (Zhao et al., 2012).–It's interesting to note that actinobacterial bacteriocins, which are peptides produced by ribosomes, may find use in agriculture (Gomes et al., 2017). This indicates that they might have a part in managing plant diseases (Gomes et al., 2017).

2.1.2. Enzymes produced by actinobacteria that involved in antibiosis against plant pathogens:

A variety of hydrolytic enzymes produced by actinobacteria are essential for antibiosis against plant pathogens. Plant diseases can be suppressed and fungal pathogens eliminated by these enzymes' ability to degrading their cell walls. Numerous studies indicate how crucial these enzymes are to biocontrol processes. According to (Bouizgarne, 2012), one of the characteristics of actinobacteria that suppresses diseases is the production of lytic enzymes. According to (Kaur et al., 2023), actinobacteria, particularly streptomycetes, demonstrate antibiosis by producing hydrolytic enzymes to fight plant diseases. Remarkably, BTU6 (*Streptomyces griseorubiginosus*) is a particular example of an actinobacterial strain that can biosynthesize β-1,3-glucanase and chitinase (Wang et al., 2021). These enzymes have been reported to be successful in degrading fungal cell walls (Wang et al., 2021). The different hydrolytic enzymes that are produced by plant growth-promoting rhizobacteria (PGPR), including actinobacteria, such as chitinase, glucanase, protease, and cellulase, are also described in detail by Jadhav et al. (2017).

2.1.3. Cell wall degrading enzymes produced by actinobacteria against plant pathogens:

Cell wall degrading enzymes (CWDEs) play an important part in plant-pathogen interactions, including both pathogens and beneficial microorganisms making these enzymes for various purposes. The following details are pertinent to actinobacteria and their possible application in controlling plant diseases: *Glutamicibacter nicotianae* AI5a and *Rhodococcus pyridinivorans* AI4 are two isolated actinobacterial strains that have been demonstrated to breakdown N-acyl homoserine lactone (AHL), a quorum sensing molecule that plant pathogens exploit (Vesuna & Nerurkar, 2020). These actinobacteria were able to inhibit the quorum sensing phytopathogen *Pectobacterium carotovorum* subsp. *carotovorum* BR1 (PccBR1) from producing enzymes that break down plant cell walls. This decrease in CWDE production prevented blackleg in a cucumber infection model and reduced soft rot symptoms in potato and cucumber maceration assays (Vesuna & Nerurkar, 2020). It's interesting to note that these actinobacteria work against plant diseases by interfering with the pathogen's capacity to make CWDEs rather than directly producing them. This mechanism, called quorum quenching, affects the pathogen's cell-to-cell communication, thus decreasing its virulence (Barnard et al., 2007; Vesuna & Nerurkar, 2020).

2.1.4. Phenols produced by actinobacteria and its role against plant pathogens.

Phenolic compounds are among the many secondary metabolites that actinobacteria, especially those in the genus Streptomyces, are known to create. These compounds are essential to plant defense mechanisms against pathogens (Ebrahimi-Zarandi et al., 2022; Hazarika & Thakur, 2020). According to Kumar et al. (2020), these phenolic compounds have antibacterial and antioxidant properties that help plants in avoiding harmful pathogenic infections and shielding tissues from the damaging effects of reactive oxygen species. Actinobacteria are efficient biocontrol agents against a variety of plant infections because they produce phenolic chemicals. For example, *Streptomyces griseocarneus* R132 successfully suppressed anthracnose symptoms caused on by *Colletotrichum gloeosporioides* in pepper plants and showed potent inhibitory effects against a variety of phytopathogens, such as *Fusarium oxysporum* and *Botryosphaeria dothidea* (Liotti et al., 2019). The generation of lytic extracellular enzymes, siderophores, and other bioactive substances, such as phenolics, is frequently credited with actinobacteria's antagonistic activity against fungal infections (Solans et al., 2016).

2.1.5. Pigments produced by actinobacteria and its role against plant pathogens.

It is well known that actinobacteria produce a wide range of pigments that are crucial to their interactions with other microbes, particularly plant diseases. Although actinobacteria-produced pigments and their function against plant diseases are not in the interesting of the studies that are offered, they do provide some relevant information on the subject. According to (Selim et al., 2021), actinomycetes are a source of pigments and other physiologically active secondary metabolites. Actinobacteria's varied bioactivities and distinctive chemical structures are a result of these pigments and other substances they produce (Selim et al., 2021). These pigments might contribute to the inhibition of plant pathogens, even though this isn't stated explicitly. Melanins are polymers with different molecular structures that usually appear brown or black and are formed by the oxidative polymerization of phenolic and indolic substances. Depending on the strain, the media, and the culture's age, actinobacteria have long been known for producing pigments that can be red, yellow, orange, pink, brownish, distinct brown, greenish brown, blue, or black (Lechevalier & Lechevalier, 1965). These brown-black metabolic polymers, also known as melanins or melanoid pigments, are significant due to their similarities to soil humic compounds as well as their utility in taxonomic research (Dastager et al., 2006 & Manivasagan et al., 2013).

2.1.6. Volatile organic compounds (VOCs)

Actinomycetes' antagonistic effect against plant diseases is mostly due to the volatile organic compounds (VOCs) they create. Numerous studies have emphasized how crucial these substances are to biocontrol methods. A *Streptomyces corchorusii* (CG-G2) strain that was isolated from rhizosphere soil shown potent antagonistic activity against *Colletotrichum gloeosporioides*, a fungal disease that causes strawberry fruit deterioration (Li et al., 2023). It was discovered that this actinomycete strain's volatile organic compounds (VOCs) were more successful than its extracts at preventing *C. gloeosporioides* spore germination and mycelial growth. The VOCs were found to contain three primary antagonistic compounds: methyl 2-methyl butyrate, hexanenitrile, and methyl 2-Ethyl hexanoate. Interestingly, methyl 2-methyl butyrate shown exceptional effectiveness in preventing fruit deterioration and maintaining fruit quality (Li et al., 2023). Examples of VOCs with antifungal activity include geosmin, 2-methylisoborneol, and methylene cyclopentane (Adra, 2024). Another example, the antifungal action of volatile organic compounds (VOCs) generated by different bacterial strains, including the generation of sulfur-containing compounds such dimethyl disulfide (DMDS), is discussed in (Rojas-Solís et al., 2017) and (Guevara-Avendaño et al., 2018). The significance of VOC extraction techniques is emphasized by (Chen et al., 2020), which shows that various extraction approaches can have a substantial impact on the effectiveness of VOC isolation from microbiological sources.

2.1.7. Other Bioactive Compounds:

A wide range of chemical structures are included in actinobacterial secondary metabolites, such as:

Polyketide (PKs) produce a broad class of substances known as polyketides. Numerous polyketides have strong antibacterial properties (Katsuyama, 2019). Some instances are *Streptomyces* sp. HAAG3-15's azalomycin B (Cao et al., 2020) and *Streptomyces griseoaurantiacus* MH191's manumycin family of compounds (Ramarajan et al., 2024).

Non-ribosomal peptide (NRPs): produces non-ribosomal peptides (NRPs), which are peptides with a variety of biological functions and complicated structures (Katsuyama, 2019). Examples include Streptomyces isolates that produce oligomycins which are effective against *Botrytis cinerea* (Louviot et al., 2024) and *Streptomyces roseoverticillatus* 63 that produces carbazomycin B (Shi et al., 2021).

Terpenoids: According to Sudha et al. (2022), terpenoids are a broad and varied class of isoprenoid substances with a range of biological activity, including antifungal capabilities. The biocontrol of sorghum grain mold infections involves terpenoids, as those produced by *Streptomyces rochei* (Sudha et al., 2022).

Additional Metabolites: Apart from antibiotics and volatile organic compounds, actinobacteria also produce a wide variety of other bioactive compounds, such as siderophores, which sequester iron and limit its availability to pathogens (Adra, 2024), (Saikia, 2022), (Faddetta, 2023). Some actinobacteria also produce indole acetic acid (IAA), a plant growth hormone that promotes plant growth and development (Gowdar, 2018), (Adra, 2024), (Saikia, 2022), (Faddetta, 2023). Actinomycetes are also a source of plant growth hormones and biopesticide compounds, according to Selim et al. (2021), which supports their role in controlling plant pathogens (Selim et al., 2021). By a variety of methods, these substances enhance the potential for overall biocontrol.

2.2. Metabolic Induction and Flexibility

A number of variables, such as the availability of nutrients, the surrounding environment, and the presence of other microbes, can affect and closely regulate the production of secondary metabolites by actinobacteria (Alwali & Parkinson, 2023; Gupta & Singhvi, 2021). Actinobacteria's capacity for biocontrol is improved by their metabolic flexibility, which enables them to modify the metabolite production in response to shifting stimulation from the environment (Ramarajan et al., 2024). Actinobacterial metabolism can be regulated to optimize their biocontrol potential by using small chemical elicitors, which can further increase the synthesis of particular secondary metabolites (Alwali & Parkinson, 2023). The production of secondary metabolites can also be influenced by the use of different culture media (Ramarajan et al., 2024; Trinidad-Cruz et al., 2024).

3. Actinobacteria Genera and Species in Biocontrol against plant pathogens bacteria & fungi

Several genera and species of actinobacteria have been found to be efficient biocontrol agents. With multiple studies showing its effectiveness against a variety of plant diseases, Streptomyces is especially well-known (Belt et al., 2021; Gowdar et al., 2018; Khan et al., 2023; Dow et al., 2023). Other genera that exhibit promise include Streptoverticillium, Amycolatopsis, Kocuria, Nocardioides, Nocardiopsis, and Saccharopolyspora (Ribeiro & Van Der Sand, 2024). *Streptomyces griseocarneus* R132 (Liotti et al., 2019), *Streptomyces tuirus* AR26 (Renuka et al., 2023), *Streptomyces djakartensis* MEPS155 (Zhang et al., 2024), *Streptomyces albidoflavus* (Mohamad et al., 2024), *Streptomyces rochei* ACTA1551 (Kanini et al., 2013), and *Streptomyces sporoverrucosus* B-1662 (Kim et al., 2024) are some of the species demonstrating interesting biocontrol activity. The wide range of efficient strains highlights actinobacteria's enormous potential for biological control. It is commonly known that actinobacteria, especially those belonging to the class Actinobacteria, have the ability to biocontrol plant diseases. In a research on endophytic actinobacteria from Korean herbaceous plants, the species Streptomyces is significantly prevalent, accounting for 45.9% of isolates (Kim et al., 2012). Micromonospora, Rhodococcus, Microbispora, and Micrococcus are other important taxa (Kim et al., 2012). Acidimicrobium, Actinomyces, Arthrobacter, Bifidobacterium, Cellulomonas, Frankia, Microbacterium, Mycobacterium, Nocardia, Propionibacterium, Pseudonocardia, Rhodococcus, Sanguibacter, and Streptomyces are among the genera of actinobacteria that have been found in a variety of environments, according to a thorough analysis (Yadav et al., 2018). Remarkably, actinobacteria linked to insects, especially ants, have demonstrated encouraging antifungal properties. The genera Nocardioidaceae, Nocardiaceae, Dermacoccaceae, Intrasporangiaceae, and Streptomycetaceae dominated the varied actinobacterial communities found in the study; 52.3% of isolates showed inhibitory activities against phytopathogenic fungi (Wang et al., 2020). According to a different study, endophytic actinobacteria from cereal plants, such as Streptomyces, Microbispora, Micromonospora, and Nocardioides species, showed notable biocontrol activity against fungal root pathogens like *Rhizoctonia solani*, Pythium spp., and Gaeumannomyces graminis var. tritici (Coombs et al., 2003).

4. Applications in Sustainable Agriculture

Actinobacteria have a wide range of potential uses in sustainable agriculture. By using them as biofertilizers, the need for chemical fertilizers can be decreased and soil health and nutrient availability can be improved (Gowdar, 2018; Saikia, 2022; Fadetta, 2023; Kaari, 2022; Silva, 2022). By reducing the risks of pesticide residues and environmental pollution, their use as biopesticides provides a secure and sustainable alternative for chemical pesticides (Ebrahimi-Zarandi, 2022), Silva, 2022, PaciosMichelena, 2021, and EkRamos, 2019). Maximizing the biocontrol efficacy of actinobacteria requires the development of efficient formulations for their delivery to plants (PaciosMichelena, 2021). Actinobacterial biopesticides' shelf life and effectiveness can be increased by employing techniques like encapsulation (PaciosMichelena, 2021). The incorporation of actinobacteria into integrated pest management (IPM) strategies has the potential to significantly improve their effectiveness (Ebrahimi-Zarandi, 2022). The combination of biocontrol agents with sustainable practices, including crop rotation and the use of resistant varieties, can result in more effective and enduring disease suppression (Ebrahimi-Zarandi, 2022). Additionally, the application of actinobacteria promotes biodiversity within agricultural ecosystems, thereby enhancing the system's resilience to environmental changes and decreasing the likelihood of pathogen outbreaks (EkRamos, 2019).

5. Limitations and Future Research

Actinobacteria have a lot of potential for biological control, but there are still a number of obstacles to overcome. It is unclear how certain actinobacteria cause systemic resistance (Ebrahimi-Zarandi, 2022), (Conn, 2008), and (Conn, 2008). To clarify these processes and clarify the specific genes and metabolites at play, more investigation is required (Ebrahimi-Zarandi, 2022), (Conn, 2008). Environmental variables including temperature, humidity, and soil pH can affect how well actinobacterial biocontrol substances work (Amaria, 2019). To maximize their effectiveness, application tactics must be tailored for various environmental situations (Amaria, 2019). Additionally, consistent techniques for assessing actinobacteria's capacity for biocontrol must be developed (Ebrahimi-Zarandi, 2022). This would make it easier to compare various strains and choose the best candidates for particular uses (Ebrahimi-Zarandi, 2022). Furthermore, studies are required to comprehend the long-term impacts of actinobacteria on ecosystem functioning and soil microbial communities (Abbasi, 2021). Maintaining soil health and ecosystem sustainability requires making sure that the use of actinobacteria does not adversely affect beneficial soil microbes (Abbasi, 2021). To find new actinobacteria and bioactive substances with improved biocontrol qualities, more biological prospecting is essential (Dinesh, 2017; Ayswaria, 2020; Selim, 2021; Qin, 2009). This entails investigating understudied ecosystems and identifying and characterizing novel compounds using advanced molecular and analytical approaches (Dinesh, 2017; Liu, 2022; Fadetta, 2023). Lastly, for actinobacterial biocontrol agents to be widely used in sustainable agriculture, research into the making efficient and affordable delivery systems is crucial (PaciosMichelena, 2021).

CONCLUSION

A promising resource for making ecologically harmless and long-lasting plant disease management techniques are actinobacteria. Their effectiveness in biocontrol is attributed to their diverse modes of action, which include antibiosis, competition, ISR, and enzyme production. A large number of new biocontrol agents can be found in the wide variety of secondary metabolites that actinobacteria produce, such as volatile organic compounds (VOCs), antibiotics, and other bioactive substances. To effectively utilize actinobacteria in sustainable agriculture, more study and development in this area is essential, even though there are still obstacles in completely understanding their mechanisms and optimizing their use. To increase the efficacy and broad acceptance of actinobacteria-based biocontrol strategies, more research is required to clarify the processes of ISR, optimize application strategies for diverse environmental circumstances, and create standardized evaluation techniques. The supply of new biocontrol agents and bioactive substances obtained from this varied species will be further expanded by investigating understudied environments and applying innovative molecular techniques.

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