JUSINDO, Vol. 7 No. 2, 2025
p-ISSN: 2303-288X, e-ISSN: 2541-7207

Streptomyces in Mangrove Ecosystems: Ecological Roles and Biotechnological Opportunities

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Keywords: *Streptomyces; mangrove ecosystem; bioactive compounds; environment; industry*

ABSTRACT

Mangrove ecosystems—saline, acidic, and oxygen-limited transition zones—host distinctive microbial consortia in which Streptomyces is prominent for its rich repertoire of bioactive secondary metabolites and pivotal ecological services. This review synthesizes evidence on the ecological functions of mangrove-derived Streptomyces and maps the biotechnological opportunities they enable, while diagnosing key constraints (difficult recovery and cultivation from extreme niches, risks of antimicrobial resistance) and proposing modern remedies. Using a qualitative literature review of studies from the past decade retrieved via major scholarly databases with keywords spanning Streptomyces, mangroves, secondary metabolites, biocontrol, biofertilizers, and bioremediation, sources were screened for relevance and methodological clarity and organized with Mendeley. The synthesis indicates that Streptomyces enhances nutrient availability through organic matter decomposition, phosphate solubilization, and siderophore production; contributes to hydrocarbon degradation and heavy-metal stabilization; and promotes plant growth and stress tolerance via phytohormones such as indole-3-acetic acid and gibberellins. Multiple strains act as effective biocontrol agents against major phytopathogens. Persisting challenges include isolation and stable cultivation under harsh physicochemical conditions and the imperative to steward antimicrobial efficacy. Advances in metagenomics reveal silent biosynthetic gene clusters, co-culture strategies awaken cryptic pathways, and bioinformatics enables genome mining and rational strain engineering to improve yield and specificity. Overall, mangrove Streptomyces constitute a strategic reservoir for sustainable innovations in health, agriculture, and environmental management, warranting an integrated agenda from in situ exploration and cross-site validation to scalable processing under robust biosafety and antimicrobial-stewardship frameworks..

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Introduction

Mangrove ecosystems act as critical transitional zones between terrestrial and marine environments, predominantly found in tropical and subtropical regions along coastlines and river mouths (Irsadi et al., 2022). These ecosystems are characterized by high salinity, low pH, and limited oxygen availability, creating challenging conditions for most organisms (Matatula, 2019). Despite these harsh environments, mangrove ecosystems support diverse microorganisms that play essential roles in nutrient cycling, organic matter decomposition, and pollutant degradation, sustaining overall ecosystem health. Among these microorganisms, Streptomyces stands out due to its significant ecological and biotechnological potential (Rusdianto et al., 2023).

As a genus of Gram-positive bacteria, Streptomyces is known for its complex metabolic capabilities and its ability to produce a wide range of bioactive compounds, including antibiotics, anticancer agents, and antioxidants. Its ecological role extends beyond secondary metabolite production, contributing to nutrient cycling, organic matter breakdown, and plant growth promotion (Goredema et al., 2020). In mangrove ecosystems, Streptomyces enhances plant resilience to environmental stressors such as high salinity and nutrient deficiency through the production of plant hormones like Indole-3-Acetic Acid (IAA) (El-Tarabily et al., 2021). Additionally, its ability to degrade organic pollutants and stabilize heavy metals underscores its importance in environmental conservation (Hu et al., 2021). Despite its vast potential, exploring and utilizing Streptomyces in mangrove ecosystems remain challenging due to the complexity of isolating and cultivating these microorganisms under extreme environmental conditions (Retnowati et al., 2023).

Understanding the ecological role and biotechnological potential of Streptomyces is essential for harnessing its full capabilities in sustainable innovation. Its contributions to nutrient cycling, organic matter decomposition, and plant growth promotion are vital for maintaining mangrove ecosystem balance. Moreover, its ability to produce bioactive compounds positions it as a valuable resource for agriculture, medicine, and environmental conservation. However, challenges in isolation and cultivation, particularly due to high salinity, low pH, and oxygen limitations, present obstacles to fully realizing its potential. Advancements in modern technology, such as metagenomics, co-cultivation, and bioinformatics, offer promising solutions for overcoming these challenges by facilitating the discovery of new bioactive compounds and optimizing Streptomyces utilization (Murray et al., 2019).

This research aims to explore the ecological importance and biotechnological potential of Streptomyces in mangrove ecosystems. It seeks to examine the role of Streptomyces in nutrient cycling, organic matter decomposition, and plant growth promotion while evaluating its potential to produce antibiotics, anticancer agents, antioxidants, and biofertilizers. Additionally, this study addresses the challenges of isolation and cultivation under extreme environmental conditions and highlights modern technological approaches to overcome these obstacles. By examining these aspects, this study contributes to understanding the multifaceted role of Streptomyces and its potential for sustainable innovations in agriculture, medicine, and environmental conservation.

Materials and Method

This study employed a qualitative research approach using a literature review method, which involved analyzing published sources or scientific materials such as journals, books, and scholarly articles deemed relevant to the research topic and objectives. Source materials were collected from various databases, including Google Scholar and Garuda, by utilizing keywords related to the research, namely Streptomyces, mangrove ecosystems, bioactive compounds, and biotechnology. The selection of materials was limited to articles published within the last 10 years that aligned with the criteria focusing on the role and potential of Streptomyces in mangrove ecosystems. Additionally, the collected articles were managed using the Mendeley application to facilitate citation management and streamline the literature review process.

Results and Discussion

The mangrove ecosystem is defined as a transitional zone between terrestrial and marine ecosystems. This ecosystem is typically found along coastlines or at river mouths in tropical and subtropical regions, consisting of plant communities dominated by mangrove species (Irsadi et al., 2022). One of the characteristics of the mangrove ecosystem is its high salinity. Salinity refers to the concentration of salt in seawater, expressed in parts per thousand (‰). Mangroves thrive in saline or brackish environments with salinity levels ranging between 11 and 25‰ (Matatula, 2019). Moreover, microorganisms play a crucial role in the mangrove ecosystem, particularly in nutrient cycling and pollutant degradation. They function as decomposers, breaking down organic matter such as mangrove leaf litter into simpler compounds, including carbon, nitrogen, and phosphorus, which can subsequently be reused by other organisms within the ecosystem (Rusdianto et al., 2023). Microorganisms in the mangrove ecosystem play a vital role in the bioremediation process, specifically in the decomposition of organic and inorganic pollutants. Certain bacteria possess specialized metabolic pathways that enable the degradation of pollutants such as hydrocarbons, petroleum, and heavy metals, thereby contributing to the maintenance of environmental quality (Rohmayani et al., 2019). Therefore, Streptomyces, a genus of bacteria commonly found in mangrove soil, has become a primary focus of research due to its ability to produce a wide range of bioactive compounds, including antibiotics, anticancer agents, and antioxidants. This capability positions Streptomyces as a promising source for the development of drugs and other therapeutic agents.

Streptomyces is a genus of Gram-positive bacteria belonging to the phylum Actinobacteria, order Streptomycetales, and family Streptomycetaceae. It forms fungus-like hyphae with aerial mycelium that develops from colonies exhibiting diverse phenotypic appearances, including granular, powdery, or velvety textures. Streptomyces produces spores and possesses complex metabolic capabilities, accounting for over 70% of known antibiotics (Goredema et al., 2020). In the nutrient cycle, Streptomyces plays a crucial role in decomposing complex organic materials, such as mangrove leaf litter, into simpler compounds that enhance nutrient availability for other organisms within the ecosystem. Additionally, extracellular enzymes produced by Streptomyces, such as amylase and cellulase, play a significant role in breaking down complex polysaccharides into simple glucose. This process increases the availability of organic carbon in the soil (Subagiyo et al., 2017). Certain Streptomyces species act as endophytic bacteria residing within mangrove tissues or as rhizosphere bacteria colonizing the root zones of mangroves. Recent research has emphasized their pivotal role in enhancing mangrove growth through the production of the plant hormone auxin. This process involves the utilization of tryptophan, a precursor found in the rhizosphere, which is metabolized into Indole-3-Acetic Acid (IAA), the primary form of auxin, subsequently absorbed by the roots. Beyond promoting growth, mangroves that receive auxin produced by Streptomyces demonstrate enhanced resilience to extreme environmental conditions, including high salinity and nutrient deficiency (El-Tarabily et al., 2021).

Streptomyces found in mangrove ecosystems is well-known for producing a wide variety of secondary metabolites, contributing to more than 70% of globally known antibiotics. For instance, it produces streptomycin, which is highly effective against both Gram-positive and Gram-negative bacteria; tetracycline, a broad-spectrum antibiotic; and rifamycin, commonly used for tuberculosis treatment. In addition to antibiotics, Streptomyces also produces anticancer and antitumor metabolites due to its potent cytotoxic activity against cancer cells. Examples include adriamycin and bleomycin, which are widely applied in chemotherapy, as well as actinorhodin, a pigmented compound with antitumor properties. Furthermore, Streptomyces synthesizes antioxidant compounds such as phenolic compounds and flavonoid-like metabolites, which can neutralize free radicals and protect cells from oxidative damage.

Other secondary metabolites produced by Streptomyces include antifungal agents such as nystatin, and erythromycin, which exhibits both antiviral and antibacterial activities (Hu et al., 2021).

Bioactive compounds produced by Streptomyces also have significant potential to support agriculture as biocontrol agents against plant pathogens. Streptomyces can induce systemic resistance (ISR) in plants after exposure to pathogens or antagonist microorganisms. A study conducted on onions demonstrated that the application of Streptomyces sp. prolonged the incubation period of moler disease. In untreated plants, the incubation period was 33 days, whereas in plants treated with Streptomyces as a biocontrol agent, the incubation period extended to 36 days. This finding indicates that Streptomyces is effective in suppressing pathogen growth through the ISR mechanism (Hadiwiyono et al., 2023). In addition to its crucial role in protecting plants from pathogens, Streptomyces also plays a significant role in promoting plant growth as a biofertilizer. Streptomyces produces the phosphatase enzyme, which has the ability to solubilize inorganic phosphate commonly found in insoluble forms in the soil. This phosphate solubilization capability is essential for facilitating key physiological processes in plants, including photosynthesis, DNA synthesis, and energy transfer, as phosphate is one of the most vital nutrients for plant development. Furthermore, certain Streptomyces species can fix atmospheric nitrogen into forms that are readily absorbable by plants, such as ammonium (NH_4^+), which is critical for leaf and stem growth. A study conducted on corn plants demonstrated that the application of Streptomyces increased phosphate availability in the rhizosphere by up to 40%, resulting in a notable positive impact on crop yields. This highlights the potential of Streptomyces as an effective biofertilizer in enhancing agricultural productivity (Chouyia et al., 2022). Streptomyces also plays a crucial role in promoting plant growth, as previously mentioned (El-Tarabily et al., 2021). In addition to producing Indole-3-Acetic Acid (IAA), Streptomyces synthesizes other growth hormones such as gibberellins, which accelerate cell division and elongation. It also produces siderophores that facilitate the solubilization and absorption of iron (Fe), an essential element for photosynthesis and overall plant metabolism. A study demonstrated that the application of Streptomyces-produced IAA increased root length by up to 25% compared to the control group (Fitriani et al., 2023). Another study reported that a specific species, Streptomyces lydicus, when integrated into a horticultural farming system, enhanced plant biomass by up to 30% (López-Reyes et al., 2024). These findings collectively underscore the multifaceted role of Streptomyces in agriculture, not only as a powerful biocontrol agent against plant pathogens but also as a biofertilizer that enhances nutrient availability and promotes overall plant growth. Its ability to improve crop resilience and productivity through multiple mechanisms highlights Streptomyces as a promising tool for sustainable agricultural practices.

Apart from its essential role in promoting plant growth and enhancing resistance to pathogens in agriculture, Streptomyces also holds significant potential in the environmental industry, particularly in bioremediation to mitigate organic pollutants and heavy metals. Its ability to decompose complex organic compounds and stabilize heavy metal contaminants establishes it as a crucial agent in sustaining environmental conservation efforts. The extracellular enzymes produced by Streptomyces are highly effective in decomposing complex organic compounds into simpler and less harmful forms. Additionally, Streptomyces has the ability to accumulate heavy metals, thereby reducing their toxicity in the environment. In the case of organic pollutants, Streptomyces can utilize various organic compounds as a single carbon source, enabling the effective degradation of pollutants. The application of Streptomyces in bioremediation offers an efficient and sustainable approach for addressing environmental contamination (Khastini et al., 2022).

Streptomyces plays a significant role in various industries, including food and health sectors, due to its broad potential in producing enzymes, probiotics, and nutraceutical compounds. In the food industry, Streptomyces is well-known for its ability to produce a wide range of extracellular enzymes that effectively break down complex structures into simpler forms, influencing the colour, taste, and texture of food products. Examples of these enzymes include amylase, protease, and lipase, which are involved in the degradation of starch, proteins, and fats, respectively (Asri et al., 2021). In addition to its enzymatic potential, Streptomyces has demonstrated promise as a probiotic through the production of oligosaccharides that act as prebiotics, supporting the growth of beneficial probiotic bacteria such as Bifidobacteria and Lactobacilli. Xylo-oligosaccharides (XOS), derived from lignocellulose biomass through the enzymatic activity of Streptomyces, have been proven to function as bioactive components in functional food products (Febrinasari & Irfan, 2023). Furthermore, Streptomyces contributes to the production of nutraceutical compounds, including antibiotics and antimicrobial agents, which play a crucial role in extending the shelf life of food products by delaying spoilage caused by pathogens. These antimicrobial compounds have been widely used in the food industry for a long time to prevent food spoilage by microorganisms (Moazzen et al., 2022). With these diverse capabilities, Streptomyces makes a substantial contribution to advancing sustainable innovation across various industrial sectors.

Although Streptomyces holds immense potential from both ecological and biotechnological perspectives, numerous challenges persist in its deeper exploration. The exploration of Streptomyces in mangrove ecosystems faces significant obstacles, particularly in isolation, cultivation, and the potential for antibiotic resistance. The unique environmental conditions of mangrove ecosystems, such as high salinity, low pH, and limited oxygen availability, create a challenging habitat for many microorganisms. Only a few microorganisms can survive and thrive under such conditions, making the isolation and cultivation process of Streptomyces highly complex. While Streptomyces is well-known for its ability to produce antibiotics, the excessive and improper use of antibiotics has led to resistance in target pathogens. This raises concerns that Streptomyces isolates from mangrove ecosystems may become less effective against resistant pathogens, ultimately diminishing their therapeutic potential (Retnowati et al., 2023).

With the advancement of modern technology, the exploration and utilization of Streptomyces have made remarkable progress through the application of metagenomics, co-cultivation, and bioinformatics. These technological advancements offer new opportunities to overcome the various challenges associated with Streptomyces exploration, particularly in extreme environments such as mangrove ecosystems, which are characterized by high salinity, low pH, and limited oxygen availability. Modern technologies not only help address the difficulties of isolation and cultivation but also contribute significantly to the discovery of novel bioactive compounds with the potential to combat antibiotic resistance. Metagenomics enables the analysis of genetic material directly from environmental samples without the need for individual organism isolation and cultivation. This approach provides unprecedented opportunities to identify previously undetected genes and biosynthetic pathways in Streptomyces that were overlooked using conventional methods. For instance, research has utilized metagenomics to uncover novel antibiotic-producing genes in Streptomyces found in extreme environments (Murray et al., 2019). Moreover, metagenomics helps mitigate the environmental challenges of mangroves by allowing researchers to explore the genetic potential of microbial communities without the necessity of successfully isolating individual organisms. In addition, co-cultivation plays a crucial role in stimulating the production of bioactive compounds that are not typically expressed in monocultures. This technique involves the simultaneous growth of two or more microorganisms, triggering the activation of cryptic biosynthetic pathways in Streptomyces, which leads to the production of novel secondary metabolites with potential biological activities. Studies have demonstrated that co-cultivation of Streptomyces with other microorganisms can significantly enhance the production of hydrolytic enzymes that are valuable in the biotechnology industry. This approach offers a promising solution to overcome the limitations of metabolite production commonly encountered in single-culture systems. Furthermore, bioinformatics is an indispensable tool for analyzing genomic and metagenomic data of Streptomyces. By leveraging bioinformatics tools, researchers can predict gene functions, identify gene clusters responsible for secondary metabolite production, and design genetic engineering strategies to enhance the yield of bioactive compounds. For example, bioinformatics analyses have been employed to map metabolic pathways in Streptomyces, facilitating the development of new antibiotics and other therapeutic agents. This technology provides profound insights that enable the optimization of Streptomyces' therapeutic potential while simultaneously addressing the growing concern of antibiotic resistance (Boruta, 2021).

Table 1. The extracted data is summarized and presented

Authors and Year	Title	Method	Key Findings	Strengrhs/ Limitation
Subagiyo et al., 2017	Potential of Mangrove Ecosystems as a Bacterial Source for Producing Protease, Amylase, and Cellulase	Experimental (Isolation and Screening)	Mangrove-derived bacteria demonstrated significant potential for producing industrially relevant enzymes such as protease, amylase, and cellulase.	**Strengths**: Highlights underexplored microbial resources. **Limitations**: Further research needed on large-scale enzyme production.
El-Tarabily et al., 2021	Rhizosphere-Competent Actinobacteria Consortium with Multiple Plant Growth-Promoting Traits Enhances Growth of *Avicennia marina*	Experimental (Field and Greenhouse)	Actinobacteria consortium improved plant growth, nutrient uptake, and stress tolerance in *Avicennia marina* in arid environments.	**Strengths**: Demonstrates application in harsh conditions. **Limitations**: Limited to specific plant species.
Hu et al., 2021	Secondary Metabolite Production Potential of Mangrove-Derived *Streptomyces olivaceus*	Experimental (Fermentation and Metabolite Analysis)	*Streptomyces olivaceus* from mangroves produced secondary metabolites with antibacterial and antifungal properties.	**Strengths**: Highlights pharmaceutical potential. **Limitations**: Requires further metabolite characterization.
Hadiwiyono et al., 2024	Compatibility and Effectiveness of *Azospirillum* and *Streptomyces* to Control Moler Disease in Shallots in Alfisol Jumantono	Field Experiment	Combination of *Azospirillum* and *Streptomyces* effectively reduced moler disease incidence and promoted plant growth in shallots.	**Strengths**: Dual benefits in disease control and growth promotion. **Limitations**: Site-specific effectiveness.
Chouyia et al., 2022	Diversity, Mechanisms, and Beneficial Features of Phosphate-Solubilizing	Literature Review	*Streptomyces* plays a crucial role in solubilizing phosphate,	**Strengths:** Comprehensive review of beneficial traits.

	Streptomyces in Sustainable Agriculture		promoting sustainable agriculture and enhancing plant nutrient uptake.	**Limitations:** Lacks field trial data.
Fitriani et al., 2023	Seed Coating with Actinobacteria to Improve Rice Plant Growth	Experimental Study (Greenhouse)	Coating rice seeds with Actinobacteria significantly increased root length, shoot height, and biomass.	**Strengths:** Practical for agricultural applications. **Limitations:** Greenhouse conditions may not replicate field environments.
López-Reyes et al., 2024	Biological Control of *Streptomyces* sp. PR69 Against *Phytophthora capsici* and Its Growth-Promoting Effects on Plants	Experimental (In vitro and Greenhouse)	*Streptomyces* sp. PR69 effectively suppressed *Phytophthora capsici* and improved plant growth by increasing root and shoot biomass.	**Strengths**: Combines biocontrol and growth promotion. **Limitations**: Needs validation in different crops.
Khastini et al., 2022	Role of Bacteria in Degrading Environmental Pollutants through Bioremediation	Literature Review	Bioremediation using bacteria effectively degrades organic pollutants and stabilizes heavy metals, maintaining environmental quality.	**Strengths**: Promotes sustainable environmental management. **Limitations**: Lacks empirical data on efficiency in different environments.
Asri et al., 2021	Fermentation of *Tape* and *Minas* from an Islamic Legal Perspective	Literature Review	Evaluates fermentation processes from an Islamic legal perspective, emphasizing acceptability in specific fermented foods.	**Strengths**: Unique perspective linking science and law. **Limitations**: Not relevant to microbiology or agriculture.
Febrinasari & Irfan, 2023	Production Technology Strategy for Xylooligosaccharides (XOS) from Agricultural Waste	Literature Review	XOS production from agricultural waste is highlighted for its prebiotic potential in functional food applications.	**Strengths**: Supports sustainable agriculture. **Limitations**: Requires large-scale production optimization.
Moazzen et al., 2022	Structure-antiradical activity relationships of 25 natural antioxidant phenolic compounds from different classes.	Experimental (Antioxidant Activity Analysis)	Established structure-activity relationship (SAR) for antioxidant compounds.	**Strengths**: Covered diverse phenolic compounds **Limitations**: No in vivo validation

				of antioxidant effects.
Retnowati et al., 2023	Antibiotic-producing *Streptomyces* sp. from mangrove soil	Experimental (Isolation & Antibiotic Assay)	Isolated *Streptomyces* with potent antibiotic activity.	**Strengths**: Highlighted mangrove ecosystem as a resource for antibiotics. **Limitations**: No genomic characterization provided
Murray et al., 2019	Emergent properties of *Streptomyces* in co-culture and genomic characterization of *Streptomyces lydicus*	Experimental (Co-culture & Genomic Analysis)	Co-culture enhanced secondary metabolite production and morphological changes.	**Strengths**: Novel insight into co-culture effects. **Limitations**: No exploration of industrial scalability.
Boruta, 2021	Bioprocess perspective on secondary metabolite production by *Streptomyces* in submerged co-cultures	Literature Review (Bioprocess Analysis)	Highlighted advantages and challenges of submerged co-culture for metabolite production.	**Strengths**: Comprehensive review on bioprocess engineering **Limitations**: Lacks case studies or experimental data.

Conclusion

Streptomyces is a crucial bacterial genus renowned for producing bioactive compounds with significant pharmaceutical, agricultural, and environmental applications. Mangrove ecosystems, characterized by extreme and unique conditions, present a promising yet challenging environment for isolating novel Streptomyces strains. Continued exploration of these habitats is essential to discover new metabolites and tackle critical issues such as antibiotic resistance. Advances in technologies like metagenomics, co-cultivation, and bioinformatics offer powerful tools to overcome the difficulties associated with isolation and cultivation, thereby unlocking new avenues for biotechnological innovation. Future research should focus on integrating these modern approaches to systematically explore mangrove-derived Streptomyces, aiming to expand metabolite diversity and develop sustainable solutions for health and environmental challenges.

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