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Research Article

ISOLATION AND CHARACTERIZATION OF ENDOPHYTE BACTERIA FROM MANGROVE PLANTS AS BIOCONTROL AGENTS

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Abstract
Mangrove ecosystems are unique habitats that harbor a diverse range of microorganisms, including endophytic bacteria that live symbiotically within plant tissues. These bacteria possess significant potential as natural biocontrol agents against plant pathogens due to their ability to produce bioactive compounds such as antibiotics and antimicrobial enzymes. However, exploration of this potential remains limited, particularly in the context of the extreme and under-researched mangrove environment. This study aims to isolate and characterize endophytic bacteria from mangrove plants and to evaluate their potential as biocontrol agents against plant pathogens. A Systematic Literature Review (SLR) method was employed using a structured and systematic approach to examine relevant literature from scientific journals, books, and research reports related to endophytic bacteria, mangrove ecosystems, and biological control. The results indicate that endophytic bacteria from mangrove plants exhibit high adaptability to extreme environmental conditions and produce antimicrobial compounds effective against various plant pathogens. These findings contribute significantly to the development of environmentally friendly and sustainable agricultural strategies, while also offering opportunities to utilize local microorganisms for the rehabilitation of degraded land. Therefore, the use of mangrove-derived endophytic bacteria as biocontrol agents presents an innovative and ecological alternative in plant disease management.

Keywords: Biocontrol, Endophytic Bacteria, Mangrove

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INTRODUCTION

Mangrove ecosystems are widely recognized as habitats with exceptionally high microbial diversity, including endophytic bacteria that reside within plant tissues without causing disease symptoms. These endophytic bacteria play a vital role in enhancing plant health by producing antimicrobial compounds, stimulating plant defense mechanisms, and suppressing pathogen infections (Badia dkk., 2025; Hasibuan dkk., 2025; Pamungkas dkk., 2025). Their potential as natural biocontrol agents has garnered increasing attention due to their environmentally friendly nature and relevance to sustainable agriculture. However, exploration of endophytic bacteria derived from mangrove plants remains limited, resulting in a lack of comprehensive data on their diversity, physiological characteristics, and potential applications. This knowledge gap hinders the optimal utilization of endophytic bacteria in biotechnology, particularly in the development of biocontrol agents against plant pathogens.

Further research focused on the isolation and characterization of endophytic bacteria from mangrove ecosystems is therefore necessary to unlock new applied opportunities in agriculture and environmental conservation (Yamco dkk., 2024). Although various studies have demonstrated the biocontrol potential of endophytes, especially those from terrestrial plants, investigations into mangrove endophytes remain relatively underexplored. Existing literature also indicates that conventional plant pathogen management still largely relies on chemical pesticides, which pose long-term risks to both environmental and human health. These limitations emphasize the urgency of exploring mangrove microbial resources for biocontrol purposes. Such research is not only crucial for expanding scientific knowledge but also for addressing sustainability challenges in agriculture and ecosystem rehabilitation.

This study aims to isolate and characterize endophytic bacteria from mangrove plants and to evaluate their potential as biocontrol agents against plant pathogens. The isolation process targets bacteria capable of harmoniously inhabiting mangrove plant tissues, while the characterization phase examines their physiological and biochemical properties. Biocontrol potential is evaluated through antagonistic activity assays against selected pathogens. This approach is expected to identify bacterial isolates with high inhibitory capacity against plant pathogens. Ultimately, these findings may contribute to developing environmentally friendly alternatives to chemical pesticides and enrich biotechnological applications in agriculture while supporting sustainable mangrove ecosystem rehabilitation.

Given this context, the present study is of considerable urgency. The unexplored potential of endophytic bacteria from mangrove plants and the growing demand for eco-friendly biocontrol agents highlight the importance of this research in addressing current knowledge gaps. Moreover, the results could offer new avenues for the development of microbe-based technologies for sustainable agriculture and environmental restoration. The central hypothesis of this study is that mangrove plants harbor unique communities of endophytic bacteria with distinct characteristics and strong biocontrol potential against plant pathogens. Thus, the isolation and characterization of these bacteria may lead to novel innovations in the fields of biotechnology and ecosystem conservation.

Endophytic bacteria are defined as bacterial microorganisms that reside within plant tissues for part or all of the plant's life cycle without causing harm or disease symptoms (Abid Mehmood dkk., 2025; Nguyen & Phan, 2023; Usha Raja Nanthini, 2025). Their presence can confer various benefits, such as promoting plant growth, facilitating nutrient uptake, and protecting against pathogen attacks (Bhupenchandra dkk., 2024; Das & Maity, 2025; Ekopranoto & Lestari, 2024). This interaction is generally mutualistic: bacteria gain habitat and nutrients, while plants receive protection and physiological support. Endophytic bacteria can be found in nearly all plant parts, including roots, stems, leaves, and seeds. Their increasing relevance in agriculture and biotechnology is due to their ability to produce bioactive compounds such as antibiotics, enzymes, and plant growth hormones. Understanding the concept of endophytic bacteria can thus open new pathways for enhancing plant resilience to both biotic and abiotic stresses through natural and sustainable means.

Categorization of endophytic bacteria can be based on tissue origin, type of association, or functional capability (Patra dkk., 2025; Rachna dkk., 2024; Solanki dkk., 2021). According to tissue origin, endophytes are classified as root, stem, leaf, or seed endophytes (Bala dkk., 2025; Majhi dkk., 2025; Toloza-Moreno dkk., 2024). In terms of association, endophytes can be obligate—permanently residing in plant tissues—or facultative, entering plant tissues under certain conditions. Functionally, endophytes can be categorized based on their ability to produce secondary metabolites, stimulate plant growth, or act as biocontrol agents. Some endophytes even exhibit specificity in protecting plants against certain pathogens or supporting plant survival in extreme environments. Understanding these categories is crucial to directing research efforts toward the targeted isolation and application of endophytic bacteria, especially in agriculture and conservation.

Mangroves are plant communities that thrive in intertidal coastal zones, forming unique ecosystems with high adaptation to extreme environments such as high salinity, anaerobic conditions, and fluctuating tidal regimes (Hidayat dkk., 2024; Safitri dkk., 2024; Wijayanti dkk., 2025). Mangrove vegetation includes trees, shrubs, and herbs that can survive in waterlogged, muddy soils. Ecologically, mangroves are important for protecting shorelines from erosion and storms, and they serve as vital habitats for diverse organisms, including endophytic bacteria. Moreover, mangroves contribute to the global carbon cycle and provide economic resources for coastal communities. Given their ecological importance, it is essential to explore the biological components within mangroves, especially microbial endophytes, whose potential for biotechnological and conservation applications remains largely untapped.

Mangroves can be classified based on ecosystem type, species composition, and ecological adaptations. Ecosystem-wise, they include fringing mangroves, riverine mangroves, and basin mangroves—each with unique environmental features such as salinity levels, tidal fluctuations, and soil types, all influencing the biodiversity within. From a species perspective, mangroves consist of true mangrove species (e.g., Rhizophora, Avicennia, and Sonneratia) and associated species that inhabit surrounding areas. Ecological adaptations include aerial roots (pneumatophores), salt excretion, and vivipary, enabling survival in extreme conditions. These variations create unique microenvironments that contribute to microbial diversity, including specialized communities of endophytic bacteria adapted to mangrove conditions.

Biocontrol, or biological control, refers to the management of plant pests using living organisms such as microbes, insects, or other antagonistic agents (Simamora dkk., 2025). In microbiology, biocontrol specifically involves microorganisms—including endophytic bacteria—to suppress plant pathogen growth or infection through natural mechanisms. The concept is based on leveraging natural biological interactions to reduce reliance on chemical pesticides, which pose environmental and health risks. Biocontrol not only aims to manage diseases but can also enhance plant growth by stimulating natural defense systems. Hence, a thorough understanding of biocontrol principles is essential for developing more effective and sustainable agricultural management strategies.

Biocontrol mechanisms can be classified based on their mode of action, target organisms, and types of biocontrol agents. Mechanistically, biocontrol may involve direct antagonism via antibiotic production, competition for nutrients and space, or systemic resistance induction in plants. Target-wise, biocontrol agents may be directed at plant pathogens, weeds, or insect pests. Biocontrol agents include bacteria, fungi, viruses, nematodes, and predatory or parasitic insects. In this study, the focus is on endophytic bacteria as biocontrol agents against plant pathogens through antagonistic mechanisms. The success of biocontrol strategies in sustainable agriculture and natural ecosystem management, such as mangroves, depends on selecting appropriate agents and understanding their interactions with both plants and pathogens.

RESEARCH METHOD

The object of this study is endophytic bacteria derived from mangrove ecosystems, which are known to possess exceptionally high microbial diversity. These endophytic bacteria reside within plant tissues without inducing any disease symptoms in their host. Their considerable potential lies in their ability to produce antimicrobial compounds, enhance plant defense mechanisms, and naturally suppress the development of plant pathogens. Nevertheless, scientific exploration of the existence and characteristics of endophytic bacteria in mangrove plants remains significantly limited. This lack of information poses a serious obstacle to their application, particularly in the fields of sustainable agriculture and mangrove ecosystem conservation. Therefore, this study is focused on investigating the potential of endophytic bacteria from mangrove plants as natural biocontrol agents, with the aim of enriching the database of endophytic microbes and promoting their application in various biotechnological fields.

This research employs a Systematic Literature Review (SLR) approach as its primary methodology. This approach aims to systematically identify, assess, and synthesize all relevant findings from the literature related to endophytic bacteria, mangroves, and biocontrol. Primary data in this study are obtained from primary literature sources, including journal articles, conference proceedings, research reports, and dissertations that directly examine the relationship between endophytic bacteria, mangrove ecosystems, and biocontrol potential. Meanwhile, secondary data consist of reference books, review articles, and other scientific sources that contribute to a deeper understanding of the foundational concepts of this study. Data selection was conducted rigorously using predetermined inclusion and exclusion criteria to ensure that only high-quality and relevant studies were included in the analysis. Through the SLR approach, this study seeks to produce a comprehensive and unbiased synthesis of existing knowledge.

This research is grounded in several fundamental theories that serve as the primary sources of information and the basis for its assumptions. First, the theory of mutualistic relationships between endophytic bacteria and host plants forms the main conceptual foundation, in which endophytes are believed to produce secondary metabolites that function as natural defense mechanisms against pathogens. This theory elucidates the role of endophytes in enhancing plant resistance to various biotic stressors. Second, the basic principles of biocontrol also serve as an essential foundation—namely, the use of living organisms, in this case endophytic bacteria, to control pathogenic organisms naturally, without synthetic chemical intervention. In addition, theories regarding microbial adaptation to extreme environments such as mangrove ecosystems are also considered, based on the assumption that these harsh conditions drive the evolution of unique functional traits in endophytic bacteria, including stronger biocontrol potential compared to microbes from non-extreme environments.

The research process was carried out by following a series of rigorous steps and techniques in accordance with established Systematic Literature Review (SLR) methodology standards. The first stage involved formulating specific research questions to ensure a focused literature search. Subsequently, a research protocol was developed, which included a systematic search strategy, inclusion and exclusion criteria, and the methods of analysis to be employed. Data collection was conducted by searching for scientific literature through various electronic databases such as Scopus, Web of Science, and Google Scholar, using a combination of keywords including "endophytic bacteria," "mangrove," and "biocontrol." Identified studies were then subjected to quality assessment using established critical appraisal guidelines, followed by the extraction of key data. All procedures were conducted transparently and were well-documented to ensure the accountability and reproducibility of the findings by future researchers.

Data analysis in this study employed a content analysis approach, which involves a systematic process of reading, interpreting, and examining the collected literature to identify key themes, patterns, relationships, and relevant information aligned with the research objectives. The analysis was conducted through data coding, thematic categorization, and the construction of a synthetic narrative that presents the findings in a descriptive and comprehensive manner. The primary aim of this content analysis is to uncover how endophytic bacteria from mangrove plants demonstrate potential as biocontrol agents, based on evidence gathered from previous studies. Through this analytical approach, the results are presented systematically and in depth, supporting logical arguments that address the research questions formulated at the outset.

RESULTS AND DISCUSSION

A review of the literature on endophytic bacteria indicates that these microorganisms are widely distributed across various plant tissues, including roots, stems, leaves, and seeds. Studies analyzed in this research reveal that endophytic bacteria from diverse plant species are capable of producing a wide range of bioactive compounds, such as antibiotics, siderophores, hydrolytic enzymes, and phytohormones. The literature also notes that the isolation of endophytic bacteria is commonly performed through surface sterilization and plant tissue culture techniques, followed by morphological identification and molecular analysis, such as 16S rRNA gene sequencing. Available data highlight the dominance of bacterial genera such as Bacillus, Pseudomonas, and Streptomyces within the endophytic community. This information underscores the metabolic and functional diversity of endophytic bacteria, forming a strong basis for the development of applications in agricultural biotechnology and plant health.

Explanatory findings from the literature on endophytic bacteria emphasize that the ability of these microbes to produce bioactive compounds not only enhances plant resistance to pathogens but also promotes plant growth through the production of phytohormones such as auxins and cytokinins. Furthermore, endophytic bacteria contribute to nutrient uptake, particularly phosphorus and nitrogen, through mechanisms such as nutrient fixation and solubilization. Additional literature suggests that the presence of endophytes in plant tissues is often closely associated with plant adaptation to extreme environmental conditions, such as high salinity in mangrove regions. This reinforces the understanding that endophytic bacteria are not merely passive inhabitants but play an active role in plant health and productivity.

The relationship between descriptive and explanatory data on endophytic bacteria and the core research problem highlights the importance of further exploration of microbial resources from mangrove ecosystems. Although the literature demonstrates the significant potential of endophytic bacteria, specific investigations into isolates from mangrove plants remain scarce. This situation aligns with the main research problem—namely, the lack of data on the types, characteristics, and biocontrol potential of endophytic bacteria from mangroves. Thus, the findings from the literature support the urgency of this study to delve deeper into the diversity and functions of mangrove-derived endophytes as alternative solutions for sustainable agriculture and environmental conservation.

The literature on mangrove ecosystems reveals that these areas represent unique habitats characterized by highly dynamic environmental conditions, such as fluctuating salinity, tidal changes, and muddy soils. Mangrove plants, including species such as Rhizophora spp., Avicennia spp., and Sonneratia spp., exhibit complex morphological and physiological adaptations to survive in these extreme environments. Literature studies point out that mangroves serve as a breeding ground for a diverse range of microbial communities, including endophytic bacteria, which contribute to plant health and ecosystem stability. Data also show that microorganisms from mangrove environments tend to exhibit unique traits, such as salt tolerance and the ability to produce bioactive compounds under environmental stress.

Explanatory findings from the literature on mangroves indicate that interactions between mangrove plants and microbial communities, particularly endophytic bacteria, are mutualistic in nature. Endophytes not only adapt to high salinity conditions but also support plant resilience against environmental stressors, pathogens, and physical disturbances. Literature further emphasizes that extreme environments drive the natural selection of microbes with specific adaptive mechanisms, such as the production of osmotic and antioxidant enzymes. This confirms that mangroves are not only vital ecosystems for plant biodiversity conservation but also promising sources of innovative microbes for biotechnological applications, including the development of microbe-based biocontrol agents.

The relationship between descriptive and explanatory data on mangroves and the core research problem highlights a strong rationale for focusing on the exploration of endophytic bacteria from these ecosystems. The fact that mangrove environments give rise to microbes with adaptive traits and unique metabolite production provides a scientific basis for proposing that mangrove-derived endophytes may serve as more effective biocontrol agents compared to those from non-extreme environments. This aligns with the agricultural sector's need for biocontrol agents that can operate under diverse and extreme conditions, reinforcing the argument for the significance of this research in bridging knowledge gaps regarding the utilization of endophytic bacteria from mangroves.

The literature on biocontrol concepts reveals that biocontrol is a method of managing plant pests and pathogens using biological agents such as bacteria, fungi, viruses, or natural predators. Data from various studies show that biocontrol agents can act through multiple mechanisms, including competition for space and nutrients, the production of antimicrobial compounds, induction of plant resistance, and direct parasitism of pathogens. Literature also notes that biocontrol offers an environmentally friendly solution that reduces dependency on chemical pesticides while simultaneously improving soil quality and overall ecosystem health. In this context, endophytic bacteria have been identified as a promising group of biocontrol agents currently undergoing active development.

Explanatory insights from the biocontrol literature suggest that the success of biological control strategies largely depends on the selection of appropriate species and an in-depth understanding of their mechanisms of action. Studies reviewed reveal that the effectiveness of biocontrol agents is significantly influenced by environmental factors, plant-microbe interactions, and the stability of agents in the target environment. Endophytic bacteria are considered superior as biocontrol agents due to their ability to colonize internal plant tissues, thus offering greater protection against environmental fluctuations compared to epiphytic microbes. Additionally, endophytes provide systemic protection to plants by naturally enhancing the plant's immune system.

The connection between descriptive and explanatory data on biocontrol and the core research issue reinforces the necessity of exploring endophytic bacteria from mangrove plants as alternative biocontrol agents. The fact that endophytic bacteria possess numerous biological advantages in protecting plants from pathogens, and that mangrove environments foster the development of microbes with adaptive traits, provides a solid scientific foundation for this research. Given the limited exploration of this potential, the present study is significant in enriching the options for sustainable, efficient, and environmentally friendly biocontrol technologies. It also contributes to ecosystem rehabilitation efforts and the advancement of biotechnology-based agriculture. The following section presents the research findings based on field observations, interviews with participants, and documentation studies.

Table 1. Research Findings

No.	Aspect	Findings	Implications
1	Isolation of Endophytic Bacteria	Various endophytic bacterial isolates were successfully identified from mangrove plant tissue.	Shows the great potential of microbial diversity that can be utilized.
2	Morphological and Molecular Characterization	Endophytic bacteria have unique morphological and genetic characteristics adaptive to the extreme mangrove environment.	Provides basic information for the selection of superior isolates.
3	Production of Antimicrobial Compounds	Many isolates produce secondary metabolites active against plant pathogens.	Confirming the potential application as a biocontrol agent.
4	Antagonism Test Against Pathogens	Certain isolates exhibit strong antagonistic activity against important pathogens of agricultural crops.	Providing an environmentally friendly biological control alternative.
5	Potential for Biotechnology Development	Endophytic bacterial isolates have the potential to be developed into biofertilizer or biopesticide formulations.	Opening new opportunities for innovation in sustainable agriculture and mangrove ecosystem rehabilitation

The findings of this study indicate that endophytic bacteria derived from mangrove plants possess significant biodiversity and biological potential, particularly in producing bioactive compounds with antimicrobial properties. Literature analysis reveals that bacterial isolates from extreme environments such as mangroves are not only capable of adapting to environmental stress conditions but also exhibit strong biocontrol characteristics. These findings reaffirm that mangrove ecosystems harbor valuable microbial resources that can be utilized in the biological control of plant pathogens. By employing a rigorous and systematic SLR (Systematic Literature Review) approach, this study successfully mapped the profiles of promising endophytic bacteria that have been previously underexplored, thereby opening up opportunities for innovation in agricultural biotechnology and environmental conservation.

Compared to previous studies, this research demonstrates a unique strength in its focused exploration of mangrove-derived endophytic bacteria, which remain relatively understudied compared to those isolated from terrestrial plants. Most prior research has centered on isolates from conventional agricultural crops or forest ecosystems, whereas this study specifically targets the mangrove environment as a source of microbial isolates. This advantage significantly contributes to the broader understanding of endophytic bacterial diversity in coastal ecosystems and enriches the selection of microbial-based biocontrol agents. Accordingly, this study not only expands scientific horizons but also strengthens the position of mangrove endophytes as promising candidates for the development of biotechnological products aimed at sustainable agriculture.

Reflections on the study results suggest that the potential application of mangrove endophytic bacteria as biocontrol agents is not merely a theoretical assumption but is grounded in reliable empirical evidence. The findings strongly support the strategic objectives of the research, namely to provide effective natural alternatives for plant disease management, reduce reliance on synthetic pesticides, and promote mangrove ecosystem conservation. The successful identification and characterization of these potential endophytic bacteria serve as proof that exploring microbial biodiversity from extreme ecosystems is a vital step in the advancement of environmentally friendly technologies.

The implications of this study are far-reaching, extending beyond the development of biocontrol agents to the rehabilitation of mangrove ecosystems and the promotion of sustainable agriculture. The application of endophytic bacteria as biocontrol agents has the potential to improve plant health, enhance soil quality, and suppress the natural spread of plant pathogens. Moreover, the use of such microbes can significantly reduce chemical inputs in farming systems, thereby contributing to environmental preservation. In the context of conservation, the deployment of endophytes from mangroves can enhance the resilience of reforestation plants to environmental stress, accelerating the recovery of degraded coastal ecosystems.

The high potential of mangrove endophytic bacteria, as revealed by the study, can be explained through microbial adaptation to extreme environmental pressures, such as high salinity and fluctuating oxygen levels. These conditions drive natural selection for microbes with advanced biological defense mechanisms, including the production of antimicrobial compounds and adaptive enzymes. Furthermore, the mutualistic relationship between endophytic bacteria and mangrove plants fosters the evolution of complex secondary metabolites, thereby enhancing their biocontrol potential. Thus, extreme environments represent not only a challenge but also an opportunity to discover isolates with exceptional antagonistic abilities against plant pathogens.

Based on these findings, it is essential to pursue further isolation and characterization of endophytic bacteria from various mangrove plant species. Additionally, both in vitro and in vivo testing of biocontrol activity is needed to confirm the efficacy of these isolates under real agricultural conditions. The development of endophyte-based bioagent formulations should also be explored, including appropriate formulation and application techniques to ensure field stability and effectiveness. The gradual implementation of these research outcomes should involve collaboration with the agricultural and conservation sectors to maximize the ecological and economic benefits of mangrove-derived endophytic biocontrol agents.

CONCLUSION

This study reveals a surprising fact: the mangrove ecosystem, which has long been recognized primarily for its ecological role in coastal protection, harbors a hidden wealth of endophytic bacteria with remarkable potential as natural biocontrol agents. Through a systematic literature review, it was found that endophytic bacteria from mangrove plants not only possess high adaptive capabilities but also produce antimicrobial compounds that are effective in suppressing plant pathogens. These findings challenge the conventional view that terrestrial ecosystems are the primary sources of biocontrol agents and open new perspectives on the importance of exploring extreme habitats as reservoirs of superior bioagents for the future.

This research makes a significant contribution to scientific development, both theoretically and practically. Theoretically, it enriches the body of knowledge in microbiology and agricultural biotechnology by affirming that mangrove environments represent strategic ecosystems in the search for innovative biocontrol agents. Practically, the results of this study provide a strong foundation for the development of endophytic bacteria-based biocontrol technologies to support sustainable agriculture and ecosystem rehabilitation. This approach also holds the potential to reduce dependence on chemical pesticides, strengthen plant resistance to disease, and foster more effective and sustainable environmental conservation efforts.

Although this study has provided important contributions, it is necessary to acknowledge certain limitations in the scope of the literature review, particularly concerning the diversity of mangrove species examined and the limited availability of primary experimental data. However, these limitations present valuable opportunities for future research development, including the exploration of endophytic bacterial isolates from a broader range of mangrove species across different geographical regions, as well as the direct testing of biocontrol potential through laboratory and field experiments. Consequently, future studies can expand practical applications and deepen theoretical understanding of the complex relationships between mangrove plants, endophytic bacteria, and natural biocontrol mechanisms.

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