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Review

Bioprospection of Endophytic Bacteria Isolated from Mangrove Ecosystems and their Potential Biotechnological Applications

[1,3]Alfian Mubaraq, [1]Mariani Sembiring, [2]Erni Widiastuti and [3,4]Mohammad Basyuni

[1]*Department of Agrotechnology, Faculty of Agriculture, Universitas Sumatera Utara, Medan, Indonesia*
[2]*Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University, Bogor District, Indonesia*
[3]*Center of Excellence for Mangrove, Universitas Sumatera Utara, Medan, Indonesia*
[4]*Department of Forestry, Faculty of Forestry, Universitas Sumatera Utara, Medan, Indonesia*

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Corresponding Author:
Mohammad Basyuni
Department of Forestry,
Faculty of Forestry,
Universitas Sumatera Utara,
Medan, Indonesia
Email: m.basyuni@usu.ac.id

Abstract: The unique mangrove ecosystem hosts a variety of microorganism activities, including the crucial role of endophytic bacteria. Microorganisms found in mangrove forests play an important role in maintaining the biosphere by uniting various living beings and can be vital for future biotechnological applications. The use of microorganisms in the field of biotechnology is prevalent for producing antimicrobials against pathogenic bacteria and as a source of drugs such as anticancer compounds, antioxidants, disease-causing antifungals, insecticides, immunosuppressants, and immune modulators. The potential of endophytic bacteria in mangrove ecosystems, which boast abundant diversity, remains largely unexplored and scientifically under-researched. This review aims to investigate various types of endophytic bacteria and summarize the potential of biotechnology employed in various aspects. The review finds that bacteria of the genera *Bacillus* and *Pseudomonas* are the most common endophytic bacteria and possess potential antimicrobial activity. The bioactive compounds found, such as L-asparaginase, function as a medical treatment for Acute Lymphoblastic Leukemia (ALL), while actinomycin D compounds have the potential to inhibit *Mycobacterium tuberculosis* the bacteria that causes Tuberculosis (TB). This study provides a broad overview of the diversity and potential of endophytic bacteria from mangrove ecosystems.

Keywords: Endophytic Bacteria, Mangrove, Biotechnology, Compound

Introduction

Mangrove ecosystems thrive in saline areas enabling mangrove plants to exhibit high tolerance to salinity compared to other plants. Mangroves grow in the border area between land and sea, along tropical and subtropical coastlines. The unique mangrove ecosystem in the intertidal area fosters genetic diversity among aquatic and terrestrial organisms that inhabit it (Gayathri *et al*., 2010; Thatoi *et al*., 2013). Mangroves can be a source of biologically potent molecules produced through plant biosynthesis and microbial interactions and can coexist with other species. Mangrove ecosystems have high ecological value, harboring a variety of organisms. They are also notable for their high productivity and cover approximately 60% of the coastline area of tropical and subtropical latitudes (Thatoi *et al*., 2013).

Mangrove forest areas play a crucial role in protecting coastal areas and their inhabitants from tides due to their strategic location at the intersection of land and sea. This makes mangrove forests a unique wetland ecosystem along the coastline (Duke *et al*., 2007). Mangroves thrive in diverse environmental conditions, withstanding tidal conditions that range from a height of less than one meter to over four meters, possessing abundant or limited nutrient availability (eutrophic), and having a warm climate that ranges from wet to arid. Their sediment types include peat and alluvial soil, with a predominance of woody plant species (Feller *et al*., 2010). Complex mangrove ecosystems can provide environmental variations that support diverse microorganisms such as bacteria involved in various activities that play a role in the nitrogen cycle, methane production, and other compound flow activities (Das *et al*., 2013). Various types

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of bacteria thrive in mangrove sediments and mangrove plant tissues, constituting abundant, freely living compositions and engaging in beneficial associations (Roy *et al*., 2002; Feng *et al*., 2009). Endophytic bacteria are a type of microorganism that live in association with plants without causing harm (Azevedo and Araújo, 2007). Mangrove ecosystems that function as habitats for several organisms including microorganisms have been the target of logging and degradation over the years. This will certainly affect the diversity of organisms that live around mangrove ecosystems (Basyuni and Sulistiyono, 2018).

Endophytes can play multiple roles in enhancing plant growth, such as producing phytohormones and growth hormones, performing nitrogen fixation, and mobilizing phosphate compounds. They can also bolster plant resistance to several diseases caused by pathogens by producing antibiotic activity (Paz *et al*., 2012; Quecine *et al*., 2008). Other studies explore their capacity for nitrogen fixation, high tolerance to heavy metals, and resilience to drought (Habibi *et al*., 2014; Doty, 2008; Dourado *et al*., 2012). Therefore, various types of endophytic microorganisms in mangrove ecosystems can be used in diverse activities, especially in the fields of biotechnology and pharmacology. These include immune modulation, vitamin production, anticancer and antimycobacterial activities, plant disease control, and high enzyme activity (Sebastianes *et al*., 2012).

Biotechnological applications of endophytic microorganisms from mangrove ecosystems are very possible and are being explored across various fields such as industry, healthcare, and food sectors (Lageiro *et al*., 2007; Sumardi *et al*., 2018). Recent technological advances have conformed to technological developments by conducting a series of molecular tests that can be used to study microbial ecology, offering a new perspective for scientists (Amann *et al*., 1995). The evolving molecular biology methods overcome the limitations of conventional identification in studying and assessing the activities of microorganism communities. As knowledge of microorganism communities continues to expand, exploration of microbial diversity and applications can be performed more extensively to benefit humans. Mangrove ecosystems, known for their unique characteristics, present greater chances of finding bacteria adapted to the complex environment of mangrove forests. This can be an important resource in producing various new compounds for biotechnology applications, making it important to explore (Sivaramakrishean *et al*., 2006). Research on endophytic bacteria and their potential in mangrove ecosystems is still very limited, necessitating a comprehensive review. Thus, the wide diversity of endophytic bacteria in mangrove ecosystems and their various environmental stresses present an interesting subject for further investigation. Further, these bacteria have potential applications in biotechnology, encompassing agriculture, health, and food industries. This review aims to explore the diversity and potential of endophytic bacteria from mangrove ecosystems.

Methods

This review covers relevant research on the diversity and biotechnological potential of endophytic bacteria found in mangrove areas. The aim was to provide a comprehensive review of this topic. Major acceptable search engines, namely Scopus and google scholar, were used to search for relevant English-language studies published from 2018 onward. The search keywords used were "bacteria", "endophytes", "mangrove" and "Indonesia". Data on mangrove host species, endophytic bacterial species, compounds found, and bacterial pharmacological activities were collected. The selected articles were assessed and interpreted. This perspective aims to provide insights into the potential of mangrove-associated endophytic bacteria for plant growth enhancement, chemical production, and biotechnology.

Endophytic Bacteria Associated with Mangroves

Endophytic Bacteria

Several studies have shown that endophytic bacteria inhabit a wide range of habitats, from tropical and subtropical regions to deserts, rainforests, mangrove ecosystems, and coastal forests (Singh *et al*., 2017). Endophytic bacteria were successfully isolated from all plant parts, such as the crown and rhizosphere areas (Senthilkumar *et al*., 2011). Endophytic bacteria have been found in various plant parts such as fruits, stems, seeds, ovules, leaves, and roots, with the roots typically hosting a more abundant population than other parts (Rosenblueth and Martínez-Romero, 2006).

Endophytic bacteria have a positive impact on their host plants, as demonstrated in studies showing their ability to produce phytohormones that promote plant growth, such as in some cereal crops, potatoes, and other agricultural crops (Mei and Flinn, 2010). Endophytic bacteria dominate and colonize various plant tissues, establishing direct contact to easily associate with plants and beneficially impact them. Likewise, endophytic bacteria gain nutritional resources from their host plant. Rhizobacteria are one such endophytic bacteria that colonize and form populations in the rhizosphere (Compant *et al*., 2010).

Methods of Endophytic Bacteria Entering Plants

The colonization mechanism of plant endophytic bacteria is influenced by several factors, such as the genes of the bacteria and host plants, as well as surrounding environmental conditions. Endophytic bacteria can infiltrate plant tissues, especially in the rhizosphere area, by exploiting wounds on plant roots or through gaps at root joints. They can also enter through plant seeds (Singh *et al*., 2017). The rhizosphere is known to be an area of strong interactions between plant roots and microorganisms in the vicinity (Bulgarelli *et al*., 2012; Robertson-Albertyn *et al*., 2017).

Physiological activities in plants, such as the production of exudates in the rhizosphere, greatly influence microorganisms around the roots. Compounds in exudates, such as organic acids, enzymes, and growth factors produced by root cell activity, play a role in the colonization of the rhizosphere by endophytic bacteria. Root exudates are considered compounds that trigger the entry of endophytic bacteria into the host plant, allowing them to form populations within plant tissues (Bulgarelli *et al*., 2012; Kawasaki *et al*., 2016; Pétriacq *et al*., 2017).

Endophytic bacteria are more abundant in the rhizosphere (10^7-10^9 cfu/g) (Benizri *et al*., 2001) than in the rhizoplasm (10^5-10^7 cfu/g) (Bais *et al*., 2006). Endophytic bacteria in the rhizosphere attach to roots, enter the root network, and colonize plant tissue (Hansen *et al*., 2006). These bacteria have been detected using the gfp/gus detection system with Fluorescence in Situ Hybridization (FISH). These techniques revealed that once inoculated into the soil, the bacteria colonize the plant rhizosphere (Gamalero *et al*., 2003). Endophytic bacteria can colonize plants grown both under in vitro conditions and in the field within the rhizoplasmic area (Compant *et al*., 2010). After colonizing the root surface and rhizodermal areas of the plant, endophytic bacteria form biofilms (Benizri *et al*., 2001).

Isolation and Identification of Mangrove Endophytic Bacteria

Most plant endophytic bacterial communities are isolated and identified through culture-dependent or culture-free methods visualized in Fig. 1. Identification of endophytic bacteria in mangrove plants can be done by taking samples from various parts of the mangrove plant, such as roots, stems, leaves, or even reproductive parts such as flowers or fruits (Rahman *et al*., 2020). Plant samples that have been taken are then sterilized to remove the exophytic bacteria on the surface of the plant. Sterilization of the sample surface was carried out using sodium hypochlorite (NaClO) with different concentrations, then the sample was washed with 70% ethanol solution at the end to remove the remnants of the chemical solution from the sample. Furthermore, the sterilized samples were then crushed to access the endophytic bacteria inside the plant tissue (Maulani *et al*., 2019).

At the stage of using the culture-dependent method, the crushed plant tissue fragments are embedded into the appropriate culture medium, usually using Nutrient Agar (NA) or Sea Water Complex (SWC) medium (Izzati *et al*., 2020). When endophytic bacteria have grown on the media, bacterial DNA extraction and DNA sequencing analysis are carried out (Rahman *et al*., 2020). The population of endophytic bacteria depends on the type of growth medium used to culture the bacteria from plant tissue. The choice of growth medium greatly affects the number and diversity of endophytic bacterial communities, because there is no single growth medium that can meet the growth requirements and nutritional values of all bacteria (Eevers *et al*., 2015). As for the no-culture method, DNA extraction from crushed plant samples is carried out and DNA sequencing techniques such as Sanger sequencing or Next-Generation Sequencing (NGS) are used to identify endophytic bacteria without the need for culture (Alhelaify *et al*., 2022).

Diversity of Mangrove Endophytic Bacteria

The type and composition of endophytic bacteria in plant tissues are greatly affected by the species and conditions of the host plant (Liu *et al*., 2017). Based on the composition of the endophytic bacteria found in host plants, *Proteobacteria* are the most abundant, comprising about 50% of the bacterial population, followed by *Firmicutes*, *Actinobacteria*, and *Bacteroidetes*, each making up about 10% of the endophytic bacterial composition. These proportions are strongly influenced by root activity and its interactions with the bacteria found in the root area. *Bacillus*, *Pseudomonas*, *Micrococcus*, and *Burkholderia* are the most common genera of endophytic bacteria found in plant hosts (Sturz and Nowak, 2000; Sun *et al*., 2008). Mangrove ecosystems have complex nutrient sources that are very rich in microbes (Sahoo *et al*., 2009).

Several studies have demonstrated the diversity of mangrove endophytic bacteria along the coastlines of the Atlantic, Indian, and Pacific oceans (Xing *et al*., 2011). However, only about 5% of this species have been scientifically described and explored (Thatoi *et al*., 2013). Several factors affect the diversity of endophytic bacteria, including the plant parts where they are found, plant age, and plant climate (Pang *et al*., 2008). Mangrove forest areas, located at the intersection of land and sea, harbor a great diversity of endophytic bacteria from soil, seawater, and freshwater microbes (Ananda and Sridhar, 2002). This review highlights several types of endophytic bacteria that have been successfully isolated and identified from various mangrove species (Table 1).

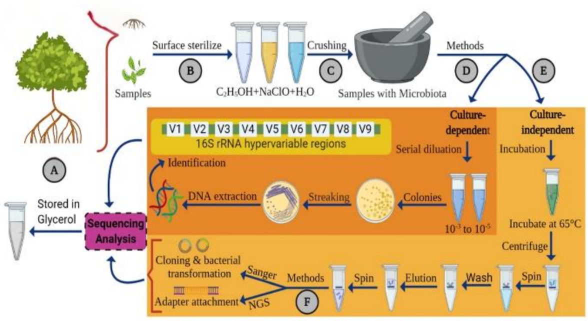

Fig. 1: Methods of isolation and identification of endophytic bacterial communities on mangroves. This model is modified from the method made by Ali *et al.* (2021): (A) sample collection; (B) standard surface sterilization of samples; (C) sample destruction

Table 1: Recent studies on the isolation of endophytic bacteria in Indonesian mangrove forests

Mangrove host plant	Geographic location	Endophytic bacteria	References
Avicennia marina	Luwuk, Central Sulawesi	*Bacillus subtilis*	Rahman *et al*. (2023)
Rhizophora apiculata	Manado, North Sulawesi	Unidentified bacteria (19 bacterial isolates)	Tangapo and Mambu (2023)
Avicennia marina	Wonorejo, Surabaya, East Java	*Bacillus subtilis* *Bacillus* sp.	Dian Savitri *et al*. (2023)
Bruguiera gymnorrhiza and Rhizopora mucronata	Enggano Island, Bengkulu	*Bacillus*, *Micrococcus*, and *Pseudomonas*	Wibowo *et al*. (2023)
Rhizophora mucronata	WanaTirta, KulonProgo, Yogyakarta	Unidentified bacteria (38 bacteria)	Nafisaturrahmah *et al*. (2022)
Mangrove ecosystem	Pramuka Island, DKI Jakarta	*Streptomyces parvus*	Rakhmawatie *et al*. (2022)
Aegiceras corniculatum, Sonneratia alba and *Avicennia alba*	Segara Anakan Lagoon, on the south coast of Java	Unidentified bacteria	Izzati *et al*. (2020)
Rhizophora mucronata	Aeng Sareh Beach, Madura Island, East Java	*Lysinibacillus fusiformis* B27	Prihanto *et al*. (2020)
R. mucronata	Gili Sulat, Sambelia District, East Lombok Regency, West Nusa Tenggara	Unidentified bacteria	Maulani *et al*. (2019)
Avicennia marina	Bojo Village, Mallusetasi Subdistrict, Barru District, South Sulawesi Province	*Vibrio* sp., *Pseudomonas* sp., and *Bacilus subtilis*	Rahman *et al*. (2020)
Avicennia marina dan Xylocarpus granatum	Serang, Banten Province	Unidentified bacteria	Rahmawati *et al*. (2019)
Avicennia alba, A. lanata, A. marina, B. cylindrica, B. gymnorrhiza, Rhizophora apiculata and *Sonneratia casiolaris*	Wonorejo mangrove forest, Surabaya, East Java	*Pseudomonas aeruginosa*, *Serratia marcescens*	Pramono *et al*. (2019)
Sonneratia alba	Bajul Mati Beach, Malang Regency, East Java	*Pseudomonas aeruginosa*	Nursyam *et al*. (2018)
Rhizophora mucronata	Jenu Beach, Tuban, East Java	*Bacillus subtilis* UBTn7	Prihanto (2018)

The genus *Bacillus* was the most prevalent among all the samples, as mentioned earlier (Liu *et al*., 2010). Ando *et al*. (2001) conducted a study in Japan where they recovered a significant number of *Bacillus* sp. from mangrove sediments. They found that these isolates have the potential to break down organic pollutant chemicals by fermentation. Several species of *Bacillus* have been found in fish, mollusks, sediments, and marine waters in Canada (Schulze *et al*., 2006). Ravikumar *et al*. (2010) obtained many endophytic bacteria from halophytic plants in the Pichavaram mangrove forest in India. Within the group of samples, the researchers discovered two types of microorganisms that live inside plants, known as endophytes. These endophytes, specifically *Bacillus thuringiensis* (MB4) and *B. pumilus* (MB8), demonstrated the ability to effectively suppress the growth of several harmful bacteria and fungi. The endophytic strain *B. amyloliquefaciens* (RS261) is a biological agent obtained from the leaves of *R. stylosa* (Feng *et al*., 2009).

Role of Mangrove Endophytic Bacteria

Microbes are vital constituents of the mangrove ecosystem and play a crucial role in establishing and preserving this biosphere, while also serving as a significant source of biotechnology products. Potential applications of endophytic bacteria isolated from mangroves are represented in Fig. 2. Mangrove ecosystems harbor a significant abundance of microorganisms that serve as a primary reservoir for antimicrobial agents. Additionally, these microorganisms synthesize a diverse array of crucial pharmaceutical chemicals, such as enzymes, anticancer agents, insecticides, vitamins, immunosuppressants, and immunological modulators (Thatoi *et al*., 2013). Table 2 provides a concise compilation of bioactive chemicals produced by endophytic bacteria and their corresponding pharmacological activity.

Bioactive Compounds in Mangrove Endophytic Bacteria

Secondary metabolites produced by endophytic microorganisms are used by host plants as defense material against attacks by other organisms (Brader *et al*., 2014) and as interaction material between endophytic bacteria and their host plants (Neher *et al*., 2009). Furthermore, endophytic bacteria also assist host plants by facilitating phytohormones, helping in plant growth and development (Tapia *et al*., 2016). Additionally, these bacteria produce secondary metabolites that can function as antimicrobials on pathogenic bacteria and as regulators for host plants. In addition, research findings show that endophytic bacteria can produce various vitamins, such as vitamin B12 and B1, alongside bioprotectants (Ivanova *et al*., 2006; Mercado-Blanco and Bakker, 2007; Trotsenko and Khmelenina, 2002). Several secondary metabolite compounds derived from endophytic bacteria, due to the activities of bioactive compounds such as peptides, flavonoids, phenols, and terpenoid derivatives, can function as antioxidants, anticancer, antibacterial and antifungal agents (Korkina, 2007). Mangroves, as a unique ecosystem, also harbor various secondary metabolite compounds, including terpenoids, phenolics, triterpenoids, and several chemical compounds such as amino acids, aliphatic acids, carotenoids, lipids, and pheromones (Revathi *et al*., 2013).

Biological and Pharmacological Activities of Mangrove Endophytic Bacteria

Research is focused on higher plants to find endophytic bacteria with 300,000 species of higher plants suggesting that each host has one or more types of endophytic bacteria (Strobel *et al*., 2004). Endophytic microorganisms and their host plants together produce bioactive compounds that have significant potential in biotechnology (Heinig *et al*., 2013). These microorganisms and their host plants interact using signals from compounds produced by endophytic microorganisms, indicating that these bioactive compounds are not toxic to the host plant (Alvin *et al*., 2014). Shukla *et al.* (2014) demonstrate that mangrove endophytic bacteria possess a variety of potential biological activities, including anti-inflammatory, antibacterial, antifungal, and antioxidant, as well as applications in the health sector as antidiabetic and anti-Alzheimer's disease.

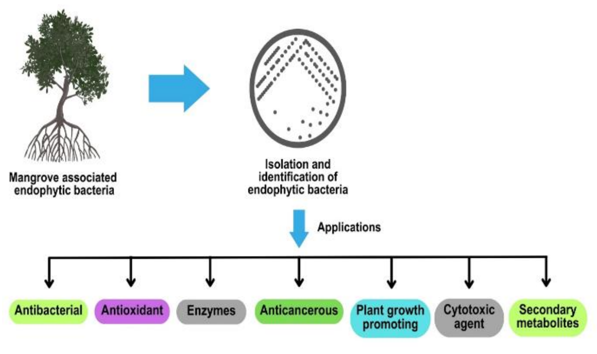

Fig. 2: Potential application of endophytic bacteria isolated from mangroves

Anti-Cancerous

Various bioactive substances synthesized by endophytes have been recognized as anti-cancer medicines (Firáková *et al*., 2007). *Bacillus* is the initial source of the first discovered anti-tumor Eksopolisakarida (EPS) a natural substance with significant therapeutic potential as a new anti-cancer agent (Chen *et al*., 2013). L-asparaginase facilitates the transformation of L-asparagine, which is necessary for the operation of some cancerous cells, like lymphoblasts. L-Asparaginase has been incorporated into multi-drug chemotherapy regimens for treating acute lymphoblastic leukemia in both children and adults, leading to notable enhancements and complete remission in the majority of patients (Piątkowska-Jakubas *et al*., 2008). Endophytic strains of *B. licheniformis*, *B. pseudomycoides*, and *Paenibacillus denitriformis* demonstrated high productivity of L-asparaginase (Joshi and Kulkarni, 2016). Nafisaturrahmah *et al*. (2022) found six bacterial colonies in the roots, 12 in the stems, and 20 in the leaves of mangroves located in the transitional zone between the sea and land. Importantly, all of these colonies exhibited positive L-asparaginase activity. L-asparaginase is a recommended medical intervention for the treatment of Acute Lymphoblastic Leukemia (ALL) and other malignancies. Bacteria are the optimal source of L-asparaginase due to their ease of cultivation, which facilitates the extraction and purification of the enzyme. Prihanto *et al*. (2020) conducted a study demonstrating the potential of the bacterium *Lysinibacillus* fusiformis B27, isolated from *Rhizophora mucronata*, to be enhanced for L-asparaginase production. By optimizing factors such as pH, temperature, and inoculum, the production of the L-asparaginase enzyme can be increased approximately threefold.

Antibacterial

Infections significantly contribute to global mortality rates, particularly in tropical places like Indonesia. Antibiotics are used to treat infectious disorders caused by pathogenic bacteria. Nevertheless, prolonged and low-dose administration of antibiotics might lead to the development of resistance in harmful microorganisms. This resistance can arise as microbes can remove specific drug targets across multiple generations (Kanungo, 2002). Mangrove plants hold significant promise as sources of pharmaceuticals, insecticides, and pesticides. Endophytes produce novel antimicrobial metabolites, providing an alternative solution to combat the growing drug resistance among human infections. This is of significant interest to the scientific community, as infectious diseases are a major cause of global human mortality (Alvin *et al*., 2014). A study was conducted to investigate the antibacterial properties of *R. mucronata* Lam leaf extract against bacteria responsible for causing diarrhea. The findings revealed that the methanol extract of *R. mucronata* Lam leaves effectively suppressed the growth of *Escherichia coli*, *E. coli* enteropatogenik (EPEC), *Staphylococcus aureus*, *P. aeruginosa* and *Salmonella typhimurium* bacteria (Tarman *et al*., 2014). Many endophytic bioactive compounds from mangroves have been found to show a broad spectrum against various pathogenic bacteria, acting as antioxidants and cytotoxic agents (Table 2), including *Escherichia coli*, *S. aureus*, *B. cereus*, and *P. aeruginosa* (Maulani *et al*., 2019). Rahman *et al*. (2023) conducted a study demonstrating the effectiveness of *Avicennia marina* mangrove leaf fermentation liquid in managing ice-ice disease caused by *Stenotrophomonas maltophilia*. The treatment that yielded optimal control and growth involved fermentation liquid enriched with Bacillus subtilis and a soaking time of 2 h. According to Vary *et al*. (2007), one of the utilizable endophytic bacteria is *Bacillus megaterium*, from the Firmicutes group. *B. megaterium* can produce Oxetanocin compounds that can inhibit Hepatitis B Virus (HBV) DNA synthesis. Shimada *et al*. (1986) found that the *B. megaterium* strain NK84-0218 exhibited potent antibacterial effects against *S. aureus*, *B. subtilis*, and *B. polymyxa*.

Anti Mycobacterial

The emergence of multidrug-resistant strains of the tuberculosis bacillus has elevated tuberculosis to a significant health risk. Consequently, there is a need to explore alternative sources of medications, such as natural products, to combat this problem (Pan *et al*., 2011). Rakhmawatie *et al*. (2022) found that the presence of the NRPS gene, which is 93% linked to the NRPS gene of *Streptomyces parvulus*, was correlated with the successful isolation of bacteria using isolate InaCC A758. Antimycobacterial studies conducted on InaCC A758 demonstrated its ability to suppress *Mycobacterium tuberculosis* the bacteria that cause Tuberculosis (TB). Two antimycobacterial active compounds were identified through fractionation and purification of the ethyl acetate extract of InaCC A758. Compound 1 ($C_{12}H_{18}ClNO_2S$; m/z 275.0723) is believed to be a dimethenamid-like compound and exhibited an MIC value of 100 µg/mL, while compound 2 ($C_{62}H_{86}N_{12}O_{16}$; m/z 1254.6285) was identified as actinomycin D.

Antioxidants

Antioxidants have been considered promising agents for the prevention and treatment of Reactive Oxygen Species (ROS) related diseases, such as cancer, heart disease, atherosclerosis, hypertension, ischemia reperfusion injury, diabetes mellitus, neurodegenerative diseases (such as Parkinson's and Alzheimer's), rheumatoid arthritis and ageing (Valko *et al*., 2007). Research by Izzati *et al*. (2020) revealed that endophytic bacteria isolated from *Avicennia alba Blume*, *Sonneratia alba* Sm., and *Aegiceras corniculatum* (L.) Blanco showed promise as both cytotoxic and antioxidant agents. The best cytotoxic action was exhibited by isolates from *A. corniculatum* fruit, while the best antioxidant activity was displayed by isolates from *A. alba* leaves. Strong antioxidant activity is essential for mangrove species and their endophytes to survive in these environments. Huang *et al*. (2007) suggested that extracts with stronger antioxidant action may contain more flavonoids and phenolic chemicals. These substances function as single electron donors and reducing agents to stabilize ROS.

Table 2: Recent research on bioactive compounds from endophytic bacteria in mangrove ecosystems and their pharmacological activity

Endophytic bacteria	Bioactive compounds	Pharmacological activity found	References
Bacillus subtilis	Substances growth-promoting	Antibacterial against *Stenotrophomonas maltophilia*	Rahman *et al*. (2023)
18 bacterial isolates	Proteolytic and cellulolytic activity	Gydrolytic enzym	Tangapo and Mambu (2023)
Bacillus subtilis, *Bacillus* sp.,	Amilase and permease	*Bacillus* is sensitive to 30 µg tetracycline	Dian Savitri *et al*. (2023)
Bacilus, *Micrococcus*, and *Pseudomonas*	Catalase enzyme	Antibacterials against pathogenic	Wibowo *et al*. (2023)
Unidentified bacteria) (38 bacteria	L-asparaginase enzyme	-	Nafisaturrahmah *et al*. (2022)
Streptomyces parvus	Actinomycin D	Antimycobacterial activity against Mycobacterium tuberculosis H37Rv	Rakhmawatie *et al*. (2022)
Unidentified bacteria	Antioxidant	Cytotoxic agent	Izzati *et al*. (2020)
Lysinibacillus fusiformis B27	L-asparaginase	-	Prihanto *et al*. (2020)
Unidentified bacteria	-	Antibacterials against pathogenic bacteria	Maulani *et al*. (2019)
Vibrio sp., *Pseudomonas* sp., and *Bacilus subtilis*	AHL-lactonase	Inhibition to *Stenotrophomonas maltophilia* bacterium	Rahman *et al*. (2020)
Unidentified bacteria	-	Antioxidant	Rahmawati *et al*. (2019)
Pseudomonas aeruginosa, *Serratia marcescens*	Amylase, protease and cellulase	Antibacterial	Pramono *et al*. (2019)
Pseudomonas aeruginosa	Gelatinase	Antibiotic	Nursyam *et al*. (2018)
Bacillus subtilis UBTn7	L-methioninase	-	Prihanto (2018)

Conclusion

Endophytic bacteria are symbiotic microorganisms that reside within plant tissues, capable of enhancing plant growth and development, even under challenging environmental situations. Derived from diverse habitats, including mangroves, terrestrial environments, and marine ecosystems, these bacteria offer a promising avenue for exploring novel bioproducts and resources with significant biotechnological potential. Mangrove ecosystems as hosts for endophytic bacteria that have high potential must be maintained. Degradation of mangrove habitats, such as logging or pollution, can disrupt and lead to a decrease in endophytic bacterial diversity. Endophytic bacteria will not grow in unfavorable habitat conditions of mangrove ecosystems. Most endophytic bacteria exhibit advantageous effects, such as the synthesis of bioproducts, phytohormones, and enzymes that have many practical uses. They are also considered formidable contenders for the biological control of antagonists in their natural environments. The application of bioproducts derived from microbes, specifically endophytic bacteria, offers an alternative approach to replacing synthetic compounds and effectively combating disease resistance caused by pathogens. One such application involves utilizing endophytic bacteria as biofertilizers to enhance plant growth. Further investigation is required to study how endophytic bacteria and their valuable metabolic products can integrate into biopharmaceutical, agricultural, and industrial applications. Additionally, the relationship between endophytic bacteria, plant physiology, and metabolism remains inadequately understood. It is unclear how endophytic bacteria utilize primary and secondary metabolites as nutrients and precursors to produce new compounds or enhance existing secondary metabolites. Hence, it is imperative to conduct sophisticated research to optimize their utilization and develop them into commercially viable products.

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Author’s Contributions

Alfian Mubaraq: Conceptualized the study, conceived and designed the analysis, collected the data, and wrote the manuscript.

Mariani Sembiring: Contributed to written the manuscript proofread and edited the final drafted of the study.

Erni Widiastuti: Collected and analyzed the data and wrote the manuscript.

Mohammad Basyuni: Conceptualized the study, contributed to wrote the manuscript, proofread and edited the final draft of the study, and submitted the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

Competing Interest

The authors report no conflicts of interest regarding this study.

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