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Bioactive Potential of Marine Biota (Algae, Sponges, and Marine Bacteria) as a Source of Antimicrobial Compounds

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Abstract

Antimicrobial resistance has become one of the most serious global health threats, prompting the search for new natural sources of antibiotics. Marine biota, such as algae, sponges, and bacteria, are known to produce a variety of secondary metabolites with potential biological activity, particularly as antimicrobial compounds. This review article examines the bioactive potential of these marine biota as an alternative source of natural antibacterial compounds. The study was conducted by reviewing various international and national literature related to the bioactive metabolites produced, their mechanisms of action against pathogenic bacteria, and the potential for their use in developing new antibacterial agents. The results of the review indicate that sulfated polysaccharides, terpenoids, alkaloids, and phenolic compounds from algae; alkaloids, cyclic peptides, and terpenoids from sponges; and secondary metabolites of marine symbiont bacteria have significant antibacterial activity, including against antibiotic-resistant bacteria. However, the development of marine bioactive compounds still faces various obstacles, particularly related to isolation techniques, mass production, and environmental sustainability issues. Therefore, modern biotechnological approaches, such as genomics, metabolomics, and synthetic biology, are needed to optimize the utilization of these marine resources. This article confirms that marine biota are important candidates for the development of new, sustainable antibacterial agents and have the potential to support the strengthening of the blue economy concept.

1. INTRODUCTION

Bacterial resistance to conventional antibiotics has become one of the most serious global health threats of the 21st century. The World Health Organization (WHO) has designated antimicrobial resistance as a "silent pandemic" because it causes treatment failure, increased morbidity and mortality, and significant economic losses (Cathartica et al., 2025). A recent report estimates that more than 1.27 million deaths annually are directly linked to antibiotic resistance, and this number is predicted to increase unless new therapeutic alternatives are discovered (Murray, 2022). This situation has driven the need to search for more effective, sustainable, and environmentally friendly sources of antimicrobial compounds.

In recent decades, the ocean has become a primary focus for the search for new bioactive compound candidates. The ocean covers more than 70% of the Earth's surface and harbours extraordinary biodiversity, including algae, sponges, and marine microorganisms capable of producing unique secondary metabolites with high biological activity (Carrol et al., 2025). Extreme marine environments, with high hydrostatic pressure, varying salinity, temperature fluctuations, and limited light, encourage marine organisms to develop adaptive mechanisms by producing chemical compounds not commonly found in terrestrial organisms (Gallo & Aulitto, 2024). These metabolites often possess novel chemical structures with antimicrobial mechanisms of action distinct from conventional antibiotics, potentially addressing resistance issues.

Marine algae, for example, are rich in phenolic compounds, terpenoids, and alkaloids, which can inhibit the growth of pathogenic bacteria (Kumar et al., 2025). Marine sponges (Porifera) are a major source of secondary metabolites with high structural diversity, including alkaloids, peptides, and polyketides, which have been tested for antibacterial, antifungal, and even antitumor activity (Nugraha et al., 2023). On the other hand, marine microorganisms, particularly actinomycetes such as Streptomyces and Salinispora, have been shown to produce natural antibiotics such as salinosporamide A and marinomycin, which are active against multidrug-resistant bacteria (Chen et al., 2021; Subramani & Sipkema, 2019). As a mega-biodiverse country with vast marine territory, Indonesia has great potential for developing marine bioprospecting. Various local studies have identified bioactive compounds from the macroalgae Sargassum sp., marine sponges, and associated bacteria that exhibit antimicrobial activity (Afreen et al., 2023; Rosari et al., 2024). However, the utilization of this potential is still limited to the initial exploration stage and has not yet been widely developed towards application or commercialization.

Based on this background, this article aims to provide a comprehensive review of marine biota's bioactive potential, especially algae, sponges, and marine bacteria as sources of antimicrobial compounds. This review will discuss the types of compounds produced, their mechanisms of action against pathogenic bacteria, challenges in development, and prospects for their application in addressing the future antibiotic resistance crisis.

2. RESEARCH METHODS

This article was compiled using a literature review approach aimed at analysing and synthesizing research results related to the bioactive potential of marine biota, particularly algae, sponges, and marine bacteria, as sources of antimicrobial compounds. The literature was collected through searches of international and national scientific databases, including PubMed, ScienceDirect, SpringerLink, Google Scholar, and Garuda (Indonesia's Digital Reference Centre). Keywords used in the search included combinations of the terms "marine bioactive compounds," "seaweed antibacterial," "sponge secondary metabolites," "marine bacteria antimicrobial," and "Indonesian marine biodiversity." The literature reviewed was limited to publications from 2000 to 2024, emphasizing the most recent research within the last ten years to obtain a more up-to-date overview. However, some classic literature was included as a theoretical basis.

Inclusion criteria for this review included original research articles, review articles, and survey reports that explicitly discussed the antimicrobial activity of compounds isolated or extracted from marine biota. Meanwhile, exclusion criteria included non-scientific publications, articles without empirical data, and research irrelevant to the antimicrobial focus. All obtained literature was then analysed qualitatively to identify the types of marine biota studied, the groups of bioactive compounds produced, their mechanisms of action against target microorganisms, and their development prospects. Furthermore, comparisons between studies were conducted to identify similarities, differences, and research gaps that still need further investigation.

3. RESULTS AND DISCUSSION

Sea Algae

Marine algae are a group of photosynthetic organisms that play a vital role in coastal and marine ecosystems. In addition to being primary producers, algae are also known to produce a variety of secondary metabolites with broad biological activities, including antibacterial, antifungal, antiviral, antioxidant, and even anticancer activities (Kumar et al., 2025). This potential makes algae important candidates for developing new sources of bioactive compounds, especially amidst increasing antibiotic resistance.

Bioactive compounds from marine algae can be divided into several main groups: sulphated polysaccharides, phenolics, terpenoids, alkaloids, and peptides. Sulphated polysaccharides, such as fucoidan from brown algae (Sargassum, Laminaria), have been shown to inhibit the growth of both gram-positive and gram-negative bacteria by disrupting the integrity of bacterial cell membranes (Flores-Contreras et al., 2023). Phenolic compounds, which are commonly found in green and red algae, act through denaturation of bacterial cell proteins and inhibition of biofilm formation (Besednova et al., 2020). In addition, terpenoids produced by brown algae exhibit antibacterial activity by inhibiting nucleic acid synthesis (Flores-Contreras et al., 2023).

Several international studies have confirmed the potential of marine algae as a source of antimicrobial compounds. For example, research by Emelda et al. (2021) showed that the methanol extract of *Ulva lactuc*a effectively inhibited the growth of *Escherichia coli* and *Staphylococcus aureus*. Another study by Putri et al. (2023) reported that *Gracilaria gracilis* extract had significant antibacterial activity against *Pseudomonas aeruginosa*. These findings indicate that variations in the antibacterial activity of marine algae are influenced by species, growing location, and the extraction method used. Indonesia, with the second-longest coastline in the world, is rich in marine algae. Another study showed that the red alga *Halymenia durvillei* from Sulawesi waters has antibacterial activity against Escherichia coli, *Salmonella typhi, P. aeruginosa, Aeromonas hydrophila,* and *Vibrio harveyi*, which are major pathogens in shrimp farming (Kasmiati et al., 2022). Similarly, red and green algae extracts have antibacterial compounds tested in vivo and in vitro (Lomartire & Gonçalves, 2023).

In addition to their direct antibacterial activity, some algal compounds are also known to work synergistically with conventional antibiotics. A study by Ibraheem et al. (2025) showed that combining algal extract with ampicillin increased the inhibitory effectiveness against methicillin-resistant *S. aureus* (MRSA). This combination approach is highly promising because it increases antibacterial potency and reduces the required antibiotic dosage, reducing the risk of subsequent resistance. Overall, marine algae provide a rich and varied source of secondary metabolites with diverse antibacterial mechanisms of action. Future exploration of antibacterial compounds from algae needs to be directed at identifying specific active compounds, optimizing environmentally friendly extraction methods, and testing in vivo activity to unlock commercialization opportunities. With continued research support, algae have great potential to become a key pillar in developing new, more sustainable antimicrobial agents.

Sea Sponges (Porifera)

Marine sponges are one of the oldest marine invertebrate groups known as primary producers of secondary metabolites with unique chemical structures and broad biological activities. More than 30% of identified marine bioactive compounds originate from sponges and the symbiotic microorganisms that live within their tissues (Brinkmann et al., 2017). The porous structure of sponges allows the entry of various symbiotic microorganisms, including bacteria, fungi, and cyanobacteria, which contribute to the biosynthesis of secondary metabolites (Romano et al., 2022). Therefore, sponges are viewed not only as a direct source of bioactive compounds but also as a "microbial reservoir" with high pharmaceutical potential.

The bioactive compounds produced by sponges are very diverse, including alkaloids, terpenoids, polyketides, cyclic peptides, and nucleosides. Some of these compounds exhibit strong antibacterial activity against multi-resistant pathogens. A notable example is manzamine A, an alkaloid isolated from

Haliclona sp. and *Xestospongia* sp., effective against *Mycobacterium tuberculosis* and various gram-positive bacteria (Fernández et al., 2024). Furthermore, aaptamin from *Aaptos* sp. exhibits antibacterial activity by inhibiting bacterial DNA synthesis (Tailor et al., 2024). Halichondrin, first discovered in *Halichondria okadai*, also possesses antimicrobial activity, although it is better known as an anticancer drug candidate (Wang et al., 2020).

International research strengthens sponges' position as a potential source of antimicrobial agents. According to the Marine Natural Products Review by Anteneh et al. (2021), more than 200 new compounds with antimicrobial activity have been identified from sponges over the past decade. These activities include inhibition of methicillin-resistant *Staphylococcus aureus* (MRSA), *P. aeruginosa*, and *Enterococcus faecalis*. The mechanisms of action of sponge compounds vary, ranging from cell membrane damage and protein synthesis inhibition to modulation of the quorum-sensing system that regulates bacterial virulence (Díez-Vives et al., 2022).

The main challenge in developing antibacterial compounds from sponges is the low availability of natural materials because most compounds are produced in small quantities. Furthermore, there are strong indications that many compounds originate from symbiotic microorganisms, not the sponge itself, necessitating microbial culture approaches or metagenomic techniques for sustainable production (Nwachukwu & Babalola, 2022). Various strategies have been developed to overcome these limitations, such as sponge cell cultures, biosynthesis based on genetically engineered microbes, and semi-synthesis that mimics the structure of natural compounds. Marine sponges are one of the most promising sources of secondary metabolites for discovering new antimicrobial agents. Their high chemical diversity, combined with Indonesia's potential as a centre of tropical sponge biodiversity, makes sponge exploration a strategic research direction to support new drug discovery and strengthen the utilization of marine biodiversity for the blue economy.

Marine Bacteria and Associated Microbes

In addition to algae and sponges, marine microorganisms, particularly bacteria, are an important source of bioactive compounds with high antimicrobial activity. Marine bacteria live in extreme environments with high pressure, varying salinity, and limited nutrient availability. Adaptation to these conditions drives bacteria to produce unique secondary metabolites that differ from terrestrial bacteria (Giudice & Rizzo, 2022). These compounds play a role in antimicrobial competition in their habitat and have great potential for application as new antibiotics.

The most extensively explored bacterial group from the sea is the Actinobacteria, particularly the genera Streptomyces and Salinispora. Salinispora tropica, for example, produces salinosporamide A, a compound with a proteasome inhibitory mechanism active against various resistant pathogenic bacteria (Mir et al., 2023). Furthermore, mariomycin, a polyketide compound from *Streptomyces* sp., has potent antibacterial activity against MRSA and VRE (vancomycin-resistant enterococci) (De La Hoz-Romo et al., 2022). These findings suggest that the sea is a vast reservoir for new-generation antibiotics.

In addition to Actinobacteria, other bacterial groups such as Pseudomonas, Bacillus, and Vibrio produce metabolites with antimicrobial activity. Marine strains of *Bacillus subtilis*, for example, are known to produce the lipopeptides surfactin and iturin, which are active against gram-positive bacteria (Ruiz et al., 2024). Meanwhile, marine Pseudomonas produces phenazines that can inhibit the growth of *E. coli* and *Klebsiella pneumoniae* (Si et al., 2024). The mechanisms of action of these compounds are diverse, including cell membrane damage, inhibition of protein synthesis, and disruption of cell communication through the quorum-sensing system.

International studies also strengthen the potential of marine microbes as a source of antibiotics. According to data from Petersen et al. (2020), approximately 50% of new compounds with antibacterial activity discovered in the last decade originate from marine microbes, free-living in the water column and associated with marine invertebrates. Metagenomics and genome mining techniques have even revealed the presence of "gene clusters" producing large quantities of secondary metabolites previously undetectable through conventional culture (Du et al., 2023). Research on marine bacteria with antibacterial potential in Indonesia is beginning to show promising results. Asih & Kartika (2021) successfully isolated bacteria symbiotic with Sinularia sp. in the waters of Gili Labak Island, which have potential as antibacterial agents, particularly for the gram-negative bacterium *E. coli*. Another study in the *Avicennia marina* mangrove ecosystem found endophytic bacterial isolates capable of inhibiting the growth of *S. aureus* and *Salmonella typhi* (Ramadhanty et al., 2021). These findings confirm that Indonesia's marine microbial diversity is a largely underexplored resource.

A major challenge in developing antibacterial compounds from marine bacteria is the difficulty in culturing most isolates in the laboratory. It is estimated that more than 90% of marine microorganisms cannot be grown using standard culture methods (unculturable bacteria), so new approaches, such as in silico approaches, are needed to improve the functionality of probiotic strains, providing deeper insights into microbial metabolism and enabling precise probiotic optimization (Baimakhanova et al., 2025). Furthermore, the scale of bioactive compound production is still limited, necessitating the development of fermentation and genetic engineering methods to produce compounds in sufficient quantities. With advances in omics technology and modern biotechnology approaches, marine bacterial exploration is expected to yield new antibiotic candidates that are effective against resistant pathogens. Given Indonesia's position as a maritime nation with abundant marine microbial diversity, research in this area is highly strategic for supporting global health resilience and developing a marine biotechnology-based blue economy.

Challenges and Prospects for Development

Despite the enormous potential of marine bioactive compounds as a source of antimicrobial compounds, several challenges require attention in their development. These challenges can be viewed from a scientific, technical, economic, and environmental sustainability perspective.

Exploration and Isolation Challenges. Limited access to marine habitats is a major obstacle. Many marine biota, such as sponges and algae, live in coral reef ecosystems or deep waters that are difficult to reach. Furthermore, most marine microorganisms cannot be cultured using conventional methods (unculturable bacteria), making the compounds they produce difficult to further explore (Rodrigues & Carvalho, 2022). This limits the exploration of bioactive compounds to groups of organisms that are relatively easy to obtain and culture.

Production and Industrial-Scale Challenges. Most marine bioactive compounds are produced in very small quantities. For example, certain secondary metabolites from sponges are present only in nanograms to micrograms per gram of tissue (Gaudêncio et al., 2023). Industrial-scale production is difficult without fermentation technology, chemical synthesis, or genetic engineering. Furthermore, chemical synthesis processes are often complex and uneconomical, while gene-editing biotechnology requires intensive research to optimize yields.

Environmental and Sustainability Challenges. Direct exploitation of marine biota for industrial purposes has the potential to cause ecosystem damage. For example, harvesting large quantities of sponges can disrupt the ecological balance of coral reefs. Therefore, the development of bioactive compounds must consider sustainability principles, such as through the cultivation of symbiotic microbes, metabolite engineering techniques, or the use of genome-based bioprospecting methods (Gaudêncio et al., 2023).

Prospects and Development Direction. Despite various challenges, the prospects for developing marine bioactive compounds are promising. As antibiotic resistance cases increase, the need for new antibiotics is increasingly pressing. Synthetic biology approaches enable the engineering of biosynthetic pathways to increase the production of bioactive compounds on an industrial scale (Martínez-Chávez et al., 2024). As an archipelagic nation with exceptionally high marine biodiversity, Indonesia offers strategic opportunities for developing this research. Collaborative efforts between universities, research institutions, and the pharmaceutical industry are crucial to accelerate the translation of research findings into commercial products.

Furthermore, applying the blue economy concept can transform the utilization of marine bioresources as a health strategy and a driver of sustainable economic growth. With an integrated approach, challenges in exploration, production, and sustainability can be overcome. Bioactive compounds from algae, sponges, and marine bacteria have significant potential as prime candidates for discovering new antibiotics to address the global problem of antimicrobial resistance. Therefore, in-depth research and policy support are essential to optimize this potential for human health and environmental sustainability.

4. CONCLUSIONS

Marine biota, particularly algae, sponges, and bacteria, are potential sources of bioactive compounds with significant antimicrobial activity. Various studies have shown that their secondary metabolites possess diverse chemical structures and mechanisms of action capable of inhibiting the growth of human pathogens and disease-causing organisms in the aquaculture sector. This makes marine biota a prime candidate in the search for new antibacterial agents to address the growing global antibiotic resistance crisis.

However, several challenges remain to be overcome, ranging from limitations in marine organism exploration, the low availability of bioactive compounds in bulk quantities, and environmental sustainability issues resulting from exploiting biological resources. Therefore, an interdisciplinary approach that combines modern biotechnology, omics methods, metabolite engineering, and synthetic biology is needed to optimize the production of marine bioactive compounds on an industrial scale. As a mega biodiversity country, Indonesia has a significant opportunity to become a centre for bioprospecting for marine bioactive compounds. With its abundant wealth of algae, sponges, and marine bacteria, this research development will contribute to the discovery of new drugs and support the implementation of a sustainable blue economy.

Future research recommendations emphasize the need for further exploration through a systematic inventory of marine biota in various coastal and deep-sea ecosystems to discover potential sources of novel bioactive compounds. A biotechnology-based approach, such as developing symbiotic microbial cultures, genomics, and metabolomics, should also be applied to access secondary metabolites that are difficult to obtain through conventional methods. In addition, advanced activity testing, both *in vivo* and *in vitro*, is essential to ensure marine bioactive compounds' safety, efficacy, and mechanisms of action. To optimize this potential, industrial-scale development should be pursued by fostering research collaboration with the pharmaceutical, food, and aquaculture sectors, thereby accelerating product commercialization. At the same time, the principle of sustainability must be prioritized by establishing regulations and policies that ensure the responsible utilization of marine biota without causing ecosystem damage. With this strategy, marine bioactive compounds can serve as a tangible solution to combating antibiotic resistance while promoting innovation in the pharmaceutical, health, and marine-based industries.

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