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Review

Exploring the antimicrobial potential of marine seaweeds: A comprehensive review of bioactive compounds and their applications

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The global rise in antimicrobial resistance has heightened the quest for new and efficient antimicrobial agents. Marine seaweed is a rich source of several amino acids, fatty acids, and dietary fibers, as well as polysaccharides, polyphenols, pigments, and other active substances, which play crucial roles in various biological processes such as antioxidant activity, immunoregulation, and anti-inflammatory response. These diverse bioactive compounds found in seaweeds offer a promising natural source of antimicrobial substances. This review explores the antimicrobial properties of various seaweed compounds, including polysaccharides, phenolic compounds, lipids, pigments and focuses on how these chemical compounds inhibit microbial growth. The review study highlights the role of seaweed chemical compounds inhibit microbial growth and discusses their potential applications in derived compounds in combating the growing problem of drug-resistant infections as well as their potential as alternative therapeutic agents.

Key words: Marine seaweed, bioactive compounds, antimicrobial resistance, polysaccharides.

INTRODUCTION

Infectious diseases, whether new or resurfacing, that are caused by microbes are typically treated with antimicrobials. However, there has been a significant increase in antimicrobial resistance with strains showing resistance. This surge is linked to the antibiotic misuse, organ transplants, and the use of immuno-suppressive agents.

Consequently, researchers are increasingly motivated to discover new antimicrobial substances, particularly from natural sources, for use in various sectors such as pharmaceuticals, biomedical textiles, and the food industry (Gomes et al., 2022; Zerrifi et al., 2018).

Seaweed is the common name for countless species of marine plants and algae that grow in water bodies, mainly in the ocean. Seaweeds are categorized into three classes: Rhodophyta (red algae), Phaeophyta

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(brown algae), and Chlorophyta (green algae) (Nuryati and Juliadiningtyas, 2015; Aydın, 2021). From the class of red seaweed, there are many species including *Kappaphycus alvarezii* (cottonii), *Eucheuma denticulatum* (spinosum), *Sargassum fusiforme, Sargassum vulgare,* and *Ceramium rubrum*. The brown algae include *Dictyota dentata, Padina australis* and *Turbinaria conoides, Fucus vesiculosus, Laminaria digitata,* and *Ecklonia cava* (Juliadiningtyas et al., 2017). Likewise, the class of green seaweeds with antimicrobial activities includes species such as *Ulva lactuca, Enteromorpha* species, *Codium,* and others.

Seaweeds, in particular, are known to produce a wide array of bioactive compounds (Rajasekar et al., 2019), with pharmaceutical properties, such as antibacterial, antifungal, and antiviral activities (Mofeed et al., 2022; Hamed et al., 2024). These compounds show potential as new therapeutic agents referred to as antibiotics and address the global challenge of antimicrobial resistance (Pérez et al., 2016). Marine organisms, including seaweeds, inhabit complex, competitive, and often hostile environments, which drive them to produce intricate secondary metabolites (Aslam et al., 2020; Mofeed et al., 2022). Some of these metabolites have antimicrobial properties that can inhibit or limit the growth of competing microorganisms, making them valuable in the fight against antimicrobial resistance (Smith et al., 2022).

As antibiotic-resistant bacterial strains pose a significant public health threat, there is an urgent necessity to discover and develop cost-effective natural antimicrobial agents. These agents should demonstrate superior potential, have fewer side effects, excellent bioavailability, and minimal toxicity in comparison to traditional antibiotics. Recent research has highlighted the promising role of natural compounds from seaweeds in combating drug-resistant infections, emphasizing their potential as viable alternatives to conventional antibiotics. This review aims to provide a comprehensive overview of the various bioactive compounds found in seaweeds, their mechanisms of action against pathogens, and their potential applications in combating antimicrobial resistance. Additionally, the review seeks to identify gaps in the current research, particularly in the context of underexplored regions such as Tanzania, to steer future studies in developing seaweed-based antimicrobial therapies.

Bioactive compound

Many industrial processes, especially those involved in the production of food, nutraceuticals, pharmaceuticals, beauty products, cosmeceuticals, and biomedicine use seaweed/macroalgae as a valuable source of bioactive compounds (Jahan et al., 2017; Lomartire et al., 2021) due to their antiparasitic, antiviral or antibacterial properties (Irene et al., 2023; Souza et al., 2020; Milledge and Harvey, 2016).

Seaweeds are considered a potential source of bioactive compounds due to their production of a wide variety of secondary metabolites with multiple functions, varied in biological activities (Martian et al., 2022). Among the compounds found in seaweeds are carotenoids, phenolic compounds, polysaccharides, and unsaturated fatty acids (Shahidi and Rahman, 2018; Aziz et al., 2021). All of these are recognized as biologically active substances that influence antioxidant, anticancer, and antimicrobial activities (Senadheera et al., 2023; Moorthi and Balasubramanian, 2015). While these compounds exhibit a broad spectrum of activities, this review focuses on their antimicrobial properties. This is critical for addressing the global challenge of antimicrobial resistance.

Mariam et al. (2023) evaluated the antimicrobial activity and anti-virulence properties of acrylic resin containing different concentrations of *U. lactuca* (a green macroalgae) against *Streptococcus mutans.* The study found that antimicrobial activities increased when a 1% concentration of *U. lactuca* was photoactivated onto the orthodontic resin (Pourhajibagher et al., 2021).

Polysaccharides and derived oligosaccharides

Algal carbohydrates mainly consist of polysaccharides, with small amounts of disaccharides and monosaccharides (Hentati et al., 2020). The polysaccharides isolated from marine seaweeds can be neutral or acidic, and they can be linear or branched (Huang et al., 2017). These polysaccharides are found mainly in sulfated and non-sulfated forms (Ciancia et al., 2020). The main components of green, brown, and red seaweed are usually polysaccharides, which serve as storage and main structural components. The presence of various types of polysaccharides as part of the cell wall matrix is specific to each species (Goñi et al., 2020). The red, brown, and green algae are distinguished by the presence of sulfated polysaccharides with a high degree of complexity, ranging from 4 to 76% DW (Berri et al., 2017; Huang et al., 2017; Lomartire and Gonçalves, 2022). The antimicrobial activity of cell wall polysaccharides, such as alginic acid/alginates, carrageenan, and agar, and their derivatives is attributed to galactans, mannans, agar, and carrageenan, depending on the configuration of the four linked α-glucopyranosyl units.

Oligosaccharides from marine plants gain attention because of their chemical and physical properties (Zhu et al., 2020). The oligosaccharides are a structural cell wall polysaccharide of the brown algae. They are derived from the polymerization of polysaccharides, and both the oligosaccharides and polysaccharides provide protection against viral, fungal, and bacterial infections in plants.

Carrageenan

Carrageenan is a group of molecules consisting of linear sulfated polysaccharide chains with ester groups attached to the sugar units (Udo et al., 2023). It has potential applications in inhibiting infections caused by various bacteria, especially in food, due to its antimicrobial action against foodborne pathogenic bacteria. Huat et al. (2023) investigated the effects of carrageenan isolated from *K. alvarezii* on pathogenic bacteria. The carrageenan was extracted using hot water, and its antimicrobial properties were tested using the minimum inhibitory concentration (MIC) and the bacterial growth rate. The bacteria tested included *Staphylococcus aureus, Klebsiella pneumoniae, Pseudomonas aeruginosa,* and *Escherichia coli.* The results indicated that the tested sample showed no antimicrobial activity.

In another study, Madruga et al. (2020) explored the chemical modification of carrageenan polysaccharides to alter their properties. They performed carboxymethylation of kappa-carrageenan (KC) using monochloroacetic acid to produce different degrees of substitution in Carboxymethyl-Kappa-carrageenan (CMKC). These varying degrees of CMKC demonstrated antibacterial activity against *S. aureus, Bacillus cereus, E. coli,* and *P. aeruginosa*. The findings suggest that CMKC polymers could be used in pharmaceutical formulations and the development of biomaterials with antibacterial properties.

Another study found that the antibacterial activity is affected by the degree of substitution with alkyl groups. According to research by Júnior et al. (2021), a microdilution test comparing N-alkyl-kappa-carrageenan derivatives with N-alkyl-(1-deoxylactitol-1-yl)- amines revealed that the inhibitory activity depended on the degree of substitution with hydrophobic groups in the polysaccharide structure. The study showed that longer N-alkyl chains had greater antibacterial activity. Additionally, research done by Li et al. (2020) revealed that copper sulfide nanoparticle-carrageenan films used for packaging can prevent food spoilage due to microbial contamination. The study found that photochemically induced carrageenan exhibited broad-spectrum antimicrobial activity, reducing *E. coli and S. aureus* by 99.2 and 99.9%, respectively.

Agar

Agar is a mixture of at least two polysaccharides, such as agarose and agaropectin. The agar has different molecular weights, with agarose having a high molecular weight and agaropectin having a low molecular weight. It is extracted from some seaweeds such as Gelidium, Gracilaria, Pterocladia, and Gelidiella (Abraham et al., 2018).

Alginate

Alginate is a brown seaweed polysaccharide that serves as a structural component of the cell wall. It exists as insoluble acid or mixed salts, primarily calcium, with smaller amounts of magnesium, sodium, and potassium concentrated in the intracellular space. The molecular weight of alginate generally ranges between 500 and 1000 kDa. The properties of alginate, including its biocompatibility, biodegradability, non-toxicity, high mechanical strength, abundance, and excellent adsorption capacity, have established alginate-based polymeric systems as a promising material for biomedical applications such as drug delivery (Hegde et al., 2022). Alginate-based materials are reported to have antiviral and antibacterial effects, such as calcium alginate/CNFs composite materials, which demonstrated antibacterial properties against the Gram-positive *S. aureus* (Sanmartín-Santos et al., 2021).

Phenolic compounds

Phenolic compounds are a group of metabolites derived from the secondary pathways of plants, comprising flavonoids, phenolic acids, tannins, lignans, and coumarins. The compounds can be found in all plants, but with significant quantities in algae (Sirbu et al., 2019). Seaweeds are a rich source of polyphenolic compounds, including phlorotannins, bromophenols, flavonoids, phenolic terpenoids, and mycosporine-like amino acids, making them one of the largest and most widely distributed groups of seaweed phytochemicals. Plant polyphenols are secondary metabolites characterized by an aromatic ring with one or more hydroxyl groups. They exhibit antibacterial activity through various mechanisms, such as interacting with proteins and bacterial cell walls, altering the permeability of the cell membrane and cytoplasmic function, and causing loss of cellular integrity, which then results in cell death (Lobiuc et al., 2023). The antimicrobial activity refers to the ability of a compound to cause cell death. In a study conducted by Zouaoui and Ghalem (2017), three algae species were collected and extracted using methanol, diethyl ether, and chloroform. The extracts were tested against various organisms, including *E. coli* ATCC 25922, *S. aureus* ATCC 25923, *Salmonella* species, *Candida albicans,* and *Penicillium* species. The findings showed significant activity against *Salmonella* spp. and *E. coli*, as well as antifungal effects against *C. albicans*, indicating that seaweeds have potential in treating human pathogens.

Additionally, El-Manawy et al. (2019) reported that brown algae contain a high concentration of phenolic compounds, which are recognized for their strong antimicrobial properties. These compounds have been discovered to be highly effective against a variety of pathogens, such as *P. aeruginosa, C. albicans, Enterococcus faecalis,* and *S. aureus.* This finding highlights the potential of brown algae as a valuable natural resource for developing treatments against various bacterial and fungal infections.

Lipids and fatty acids

Fatty acids are the building blocks of most lipids. They consist of long hydrocarbon chains with a carboxyl group at one end. These fatty acids come in different types, such as saturated and unsaturated, depending on their length and degree of saturation. Marine organisms, particularly algae and fish, are known for containing high levels of bioactive lipids and fatty acids. Brown algae, for instance, are abundant in polyunsaturated fatty acids (PUFA), which have been demonstrated to possess antimicrobial, anti-inflammatory, and antioxidant properties. These bioactive compounds are increasingly being researched for their potential therapeutic applications in treating various diseases, as well as for their overall health benefits (Ganesan et al., 2019; Peng et al., 2022; Manivannan et al., 2008).

Pigments

Seaweeds, like other photosynthetic organisms, can produce three main types of pigments: chlorophylls, carotenoids, and phycobiliproteins. Carotenoids, which are found in all algae, are natural pigments that are soluble in lipids. They are made up of eight units of five carbons, known as tetraterpenoids, and can have up to 15 conjugated double bonds. Seaweed carotenoids could lead to the accumulation of lysozyme, an immune system component that digests the cell wall as part of its antimicrobial mechanism. Fucoxanthin, a type of carotenoid produced by brown algae, is said to have several biological properties, including antioxidant, anti-obesity, anti-diabetic, anticancer, and antimicrobial activities (Freitas et al., 2022). It was tested using the disc diffusion method, revealing a stronger antimicrobial impact against Gram-positive bacteria compared to Gram-negative bacteria (Karpiński and Adamczak, 2019).

METHODOLOGY

Review search strategy

A systematic literature search was conducted across multiple scientific databases, including PubMed, Scopus, Web of Science, and Google Scholar. The search focused on peer-reviewed articles, book chapters, and conference proceedings published between 2015 and 2024.

Inclusion criteria

1) Studies reporting on the antimicrobial properties of marine seaweed-derived bioactive compounds.
2) Research discussing the extraction, characterization, and application of antimicrobial compounds from marine macroalgae.
3) Articles published in English in peer-reviewed journals.
4) Experimental, review, and meta-analysis studies related to the antimicrobial potential of seaweeds.

Exclusion criteria

1) Studies focusing on non-marine algae or freshwater species.
2) Research on bioactive compounds without antimicrobial relevance.
3) Articles lacking experimental or detailed mechanistic insights.
4) Non-peer-reviewed articles, editorials, and opinion pieces.
5) Papers that do not follow the year between 2015 and 2024.

Search terms

This included “marine seaweeds” AND “antimicrobial activity”, “bioactive compounds” AND “marine macroalgae”, “seaweed-derived antimicrobials”, “natural antibiotics from seaweed”, “secondary metabolites from seaweeds”, “macroalgal bioactive” AND “pharmaceutical applications”, and “seaweed extracts” AND “antimicrobial resistance”.

Data extraction process

Data were extracted from the selected articles by retrieving information including seaweed species studied, types of bioactive compounds identified (e.g., phenolics, terpenoids, sulfated polysaccharides), antimicrobial activity (target microorganisms, inhibition zone, MIC values, extraction and characterization methods used, and potential applications in pharmaceuticals and biomedicine. The extracted data were organized in a spreadsheet to facilitate synthesis and comparative analysis.

Data analysis

The extracted data were analyzed using a thematic and comparative synthesis approach. Key findings were categorized based on seaweed species, classes of bioactive compounds, and their reported antimicrobial mechanisms. Trends in antimicrobial efficacy were identified by comparing results across different studies, highlighting commonalities and variations in reported activity.

RESULTS AND DISCUSSION

Diversity of seaweed species and bioactive compounds

The review identified a wide range of marine seaweed species exhibiting antimicrobial properties, primarily belonging to the Rhodophyta (red algae), Phaeophyta (brown algae), and Chlorophyta (green algae) groups. Key bioactive compounds responsible for antimicrobial activity included phenolics, terpenoids, alkaloids, sulfated polysaccharides, and halogenated compounds. These compounds were found to exhibit broad-spectrum activity against bacteria, fungi, and other microbial pathogens.

Antimicrobial activity and mechanisms

The extracted data indicated that many seaweed-derived bioactive compounds demonstrated strong antibacterial and antifungal activity, particularly against pathogenic Gram-positive and Gram-negative bacteria such as *S. aureus*, *E. coli*, and *P. aeruginosa*. The antimicrobial mechanisms varied, including cell membrane disruption, enzyme inhibition, and interference with quorum sensing and biofilm formation.

Extraction and characterization techniques

The review revealed that solvent extraction, supercritical fluid extraction, and enzymatic hydrolysis were commonly used to isolate bioactive compounds. Characterization techniques such as gas chromatography-mass spectrometry (GC-MS), high-performance liquid chromatography (HPLC), and nuclear magnetic resonance (NMR) spectroscopy were frequently employed to identify and quantify the active compounds. Differences in extraction efficiency and bioactivity were noted across studies, suggesting that optimization of extraction methods could enhance the yield and potency of antimicrobial compounds.

Potential applications in pharmaceuticals and biotechnology

The findings highlighted the promising pharmaceutical applications of seaweed-derived antimicrobial compounds, including their potential use as natural alternatives to synthetic antibiotics in combating antimicrobial resistance. Additionally, their incorporation into wound dressings, food preservatives, and biomedical coatings was noted as an emerging area of research. However, challenges such as scalability, bioavailability, and regulatory approvals were identified as key hurdles to their commercial development.

Gaps and future directions

Despite extensive research on the antimicrobial properties of seaweed bioactives, gaps remain in standardized testing methodologies, clinical validation, and large-scale production strategies. Future studies should focus on mechanistic investigations, structure-activity relationships, and in vivo efficacy assessments to bridge the gap between laboratory findings and practical applications.

CONCLUSION

This comprehensive review of marine seaweed compounds emphasizes their significant potential as natural antimicrobial agents in tackling the growing problem of antimicrobial resistance (AMR). The wide variety of bioactive compounds, including polysaccharides, phenolic compounds, lipids, and pigments, shows a multifaceted approach to inhibiting microbial growth. The diversity of these compounds, along with their unique modes of action, positions seaweeds as a valuable resource in the fight against antimicrobial resistance, offering a natural alternative to conventional antibiotics. These compounds not only demonstrate antifungal, antibacterial, and antiviral properties but also contribute to essential biological processes such as antioxidant activity and immunoregulation.

This review confirms the important role of marine seaweeds as a source of powerful antimicrobial substances. It also encourages further exploration into their mechanisms, effectiveness, and potential applications. Collaborative research and innovation will utilize the health-promoting properties of these natural resources to develop safer and more effective alternatives to conventional antibiotics.

Despite the promising results from various studies, there is still a significant research gap in exploring seaweed species from under-researched regions such as Tanzania. Local biodiversity in these areas could provide new potential antimicrobial agents. Future studies should focus on exploring the untapped diversity of local seaweed species and their compounds to develop antimicrobial treatments that are relevant to the region.

CONFLICT OF INTERESTS

The author has not declared any conflict of interests.

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