14 Potential Seaweed-Derived Bioactive Compounds for Pharmaceutical Applications

John Tsado Mathew, Abel Inobeme, Bini Muhammad Etsuyankpa, Elijah Yanda Shaba, Musa Safiyanu Tanko, Abdulkadir Abdullahi, Ismail Haruna, Jonathan Hussaini, Amos Mamman, O. B. Akinsipo, M. O. Agbugui, C. Achema, J. Osaseren, A. B. Mahmoud, and I. Dolapo

J. T. Mathew (✉) · I. Haruna · J. Hussaini · A. Mamman
Department of Chemistry, Edo University Uzairue, Auchi, Nigeria

A. Inobeme
Department of Chemistry, Ibrahim Badamasi Babangida University Lapai, Niger State, Nigeria

B. M. Etsuyankpa · M. S. Tanko
Department of Chemistry, Federal University Lafia, Nasarawa State, Nigeria

E. Y. Shaba
Department of Chemistry, Federal University of Technology Minna, Minna, Nigeria

A. Abdullahi
Department of Biochemistry, Federal University of Technology Minna, Minna, Nigeria

O. B. Akinsipo
Department of Chemistry, Tai Solarin University of Education, Ogun State, Nigeria

M. O. Agbugui
Department of Biological Science, Edo State University Uzairue, Ogbida, Nigeria

C. Achema
Department of Mathematics, Edo State University Uzairue, Ogbida, Nigeria

J. Osaseren
Department of Biochemistry, Auchi Polytechnic, Auchi, Nigeria

A. B. Mahmoud
Department of Chemistry, Nigeria Police Academy, Wudil, Nigeria

I. Dolapo
Department of Science Laboratory Technology, Osun State College of Technology, Osun, Nigeria

R. T. Kapoor et al. (eds.), *Biomass Valorization*,
https://doi.org/10.1007/978-981-97-8557-5_14

Abstract

The quest for various nutraceuticals has risen recently due to their invaluable bioactive ingredients and therapeutic properties. To this end, experts have sourced various species of plants that have high contents of bioactive compounds for their potential exploration in pharmaceutical applications. More recently, seaweeds have proven to be highly promising, hence their wide application in medicinal usage. They have been documented to contain a high amount of numerous biologically active molecules which are accountable for their antioxidant, antiviral, and antimicrobial properties. They have also been well explored in food, and cosmetic production, as well as in nutraceuticals industries. In some current investigations, seaweeds have been considered a suitable and reliable alternative to various synthetic compounds used in pharmaceutical industries. Seaweeds have varying compositions of bioactive compounds, which are dependent on factors such as the type of algae, period of harvesting, and environmental conditions. The consumption of seaweeds as a source of nutrients is due to their high mineral, vitamins, and protein compositions. This work focuses on the bioactive compounds that are derived from seaweeds and their applications in pharmaceutical industries. It discusses various bioactive compounds present in seaweeds. It highlights the antimicrobial, antiviral, and antioxidant potentials of these active ingredients. Furthermore, some recent studies on their exploration of these applications are also presented. Future perspectives in the exploration of bioactive compounds from seaweeds for pharmaceutical applications are also attempted.

Keywords

Bioactive · Compounds · Pharmaceutical · Seaweeds

14.1 Introduction

Seaweeds, also known as marine macroalgae, have long been recognized for their rich bioactive compound content and diverse pharmacological properties. This review explores the potential of seaweed-derived bioactive compounds for pharmaceutical applications. Seaweeds encompass a vast array of species with unique chemical compositions, making them a valuable resource for drug discovery and development (Jaworowska and Murtaza 2022). Polysaccharides, proteins, peptides, polyphenols, lipids, and pigments are among the bioactive compounds found in seaweeds, each exhibiting a range of beneficial effects such as antioxidant, anti-inflammatory, antimicrobial, anticancer, and wound healing properties. However, harnessing these bioactives for pharmaceutical use presents challenges, including sustainable sourcing, extraction optimization, and regulatory compliance. Nevertheless, recent advancements in extraction techniques, coupled with growing interest in natural products-based therapies, have spurred research and development efforts in this field. Case studies highlighting the successful utilization of seaweed-derived bioactives in pharmaceutical products underscore their potential as valuable

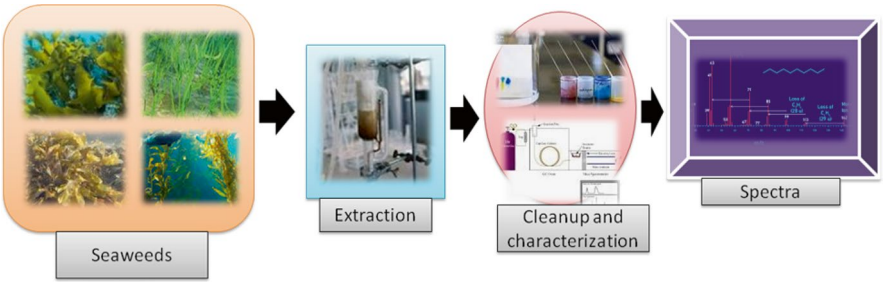

Fig. 14.1 Schematic representation of chapter

therapeutic agents (Gomez-Zavaglia et al. 2019). Addressing sustainability concerns and navigating regulatory pathways are crucial steps towards realizing the full pharmaceutical potential of seaweed bioactive. In conclusion, seaweed-derived bioactive compounds offer promising avenues for the development of novel pharmaceuticals, with implications for both human health and environmental sustainability (Afzal et al. 2023). This chapter presents potential seaweed-derived bioactive compounds for pharmaceutical applications. It starts with a general overview of seaweeds, their classes, and bioactive compositions. It discusses the various methods of extraction and characterization of their active ingredients (Fig. 14.1). It also highlights the applications of these biochemical compositions in the pharmaceutical industry. Finally, recent reports in this regard are also presented.

14.2 General Overview of Seaweeds

Seaweeds, also known as marine macroalgae, are a diverse group of photosynthetic organisms that inhabit the world's oceans and other bodies of water. Despite their name, seaweeds are not weeds at all but rather complex multicellular algae that play vital ecological roles and have significant economic and cultural importance worldwide. Seaweeds belong to the kingdom Protista within the broader classification of algae. They are classified into three main groups based on their pigmentation and cell structure: red algae (Rhodophyta), brown algae (Phaeophyceae), and green algae (Chlorophyta). Each group exhibits distinct characteristics, including coloration, size, and habitat preferences (El-Beltagi et al. 2022).

Seaweeds are found in a wide range of marine environments, from the rocky intertidal zones along coastlines to the depths of the open ocean. They can thrive in diverse conditions, including cold polar waters, temperate coastal areas, and tropical coral reefs. Seaweeds are also adapted to various substrate types, such as rocks, sand, mud, and even other organisms like corals and shells. The morphology of seaweeds varies greatly among species but typically consists of thallus structures, which may be filamentous, sheet-like, or branched, depending on the species. Seaweeds reproduce through both sexual and asexual means. Sexual reproduction involves the release of gametes (eggs and sperm) into the water, where fertilization

occurs, leading to the formation of zygotes that develop into new individuals. Asexual reproduction occurs through fragmentation, where pieces of the seaweed break off and grow into new plants, or through the production of spores that germinate into new individuals (Takao et al. 2015; Inobeme et al. 2024a).

Seaweeds play crucial roles in marine ecosystems and contribute to global biogeochemical cycles. They provide habitat and food for a diverse array of marine organisms, including fish, invertebrates, and marine mammals. Seaweeds also contribute to primary production through photosynthesis, converting carbon dioxide and sunlight into organic matter, which supports marine food webs and influences nutrient cycling in coastal ecosystems. Seaweeds have been utilized by humans for thousands of years, with cultural and economic significance in many coastal communities worldwide. They are harvested for various purposes, including food, agriculture, cosmetics, pharmaceuticals, and industrial applications. In many Asian countries, seaweeds are integral components of traditional cuisines, valued for their nutritional properties and unique flavors. Additionally, seaweeds are cultivated commercially for the production of hydrocolloids such as agar, carrageenan, and alginate, which are used as gelling agents, stabilizers, and thickeners in food, pharmaceutical, and other industries (Menaa et al. 2020; Adetuyi et al. 2024).

Despite their ecological and economic importance, seaweeds face numerous challenges and threats in today's rapidly changing world. Anthropogenic activities such as overharvesting, pollution, habitat destruction, and climate change pose significant risks to seaweed populations and marine ecosystems. In particular, rising sea temperatures, ocean acidification, and changing ocean currents can disrupt seaweed growth and distribution, leading to shifts in marine biodiversity and ecosystem dynamics. Efforts to conserve and sustainably manage seaweed resources are increasingly important in mitigating these threats and preserving the ecological integrity of marine ecosystems. Conservation strategies may include the establishment of marine protected areas, implementation of sustainable harvesting practices, regulation of coastal development, and promotion of seaweed aquaculture as an alternative to wild harvesting. Additionally, public awareness and education campaigns can help foster appreciation for the value of seaweeds and the need for their conservation (Banach et al. 2022).

Looking ahead, seaweeds are likely to play an increasingly important role in addressing global challenges such as food security, climate change mitigation, and sustainable development. Advances in seaweed cultivation techniques, biotechnology, and industrial processing hold promise for expanding the range of seaweed-derived products and applications. Furthermore, continued research into the ecological functions of seaweeds and their interactions with marine ecosystems will deepen our understanding of their importance and inform conservation and management efforts in the years to come (Pereira et al. 2024).

14.3 Classes of Seaweeds and the Bioactive Components

Seaweeds, also known as marine macroalgae, encompass a diverse array of species classified into three main groups: red algae (Rhodophyta), brown algae (Phaeophyceae), and green algae (Chlorophyta). Each class exhibits unique morphological characteristics and biochemical compositions, giving rise to a wide variety of bioactive compounds with potential pharmaceutical applications (Menaa et al. 2021).

Red algae (Rhodophyta): Red algae are characterized by their distinctive red pigmentation, which results from the presence of phycoerythrin and phycocyanin pigments, masking the green chlorophyll. They are predominantly found in marine environments, ranging from intertidal zones to deep-sea habitats. Red algae are rich sources of bioactive compounds, including polysaccharides, polyphenols, peptides, and pigments, which exhibit a range of pharmacological activities (Chen et al. 2022).

Bioactive components, polysaccharides: Red algae are renowned for their sulfated polysaccharides, such as carrageenans and agar, which possess various biological activities, including antiviral, anti-inflammatory, and anticoagulant properties. Carrageenans, extracted from species like *Chondrus crispus* and *Gigartina skottsbergii*, have been investigated for their potential as antiviral agents against herpes simplex virus and human immunodeficiency virus (HIV) (Hans et al. 2021; Inobeme et al. 2023a).

Polyphenols: Red algae contain phenolic compounds with antioxidant and anti-inflammatory properties, such as phlorotannins and flavonoids. These compounds are derived from the phenylpropanoid pathway and contribute to the defense mechanisms of red algae against environmental stressors. Phlorotannins, found in species like *Ecklonia cava* and *Sargassum* spp., have shown promise as potential therapeutic agents for various diseases, including cancer and cardiovascular disorders (Pereira and Cotas 2023).

Peptides: Red algae produce bioactive peptides with diverse physiological effects, including antimicrobial, antihypertensive, and immunomodulatory activities. Peptides derived from red algae proteins exhibit inhibitory effects against pathogens such as bacteria, fungi and viruses, making them valuable candidates for pharmaceutical applications (Elbandy 2022).

Brown algae (Phaeophyceae): Brown algae are characterized by their brownish coloration, which results from the presence of fucoxanthin pigments, masking the chlorophyll. They are primarily marine organisms, commonly found in coastal regions and cold-water habitats. Brown algae are renowned for their large size and complex thallus structures, which harbour a rich diversity of bioactive compounds with potential pharmacological benefits (El-Beltagi et al. 2022).

Bioactive components, fucoxanthin: Brown algae are the primary sources of fucoxanthin, a carotenoid pigment with potent antioxidant and anticancer properties. Fucoxanthin has attracted significant attention due to its ability to modulate various cellular pathways involved in cancer development, including apoptosis, cell cycle regulation, and angiogenesis inhibition (Mohibbullah et al. 2022).

Fucoidans: Brown algae produce fucoidan polysaccharides, sulfated polymers with diverse biological activities, including anticoagulant, antithrombotic, anti-inflammatory, and antiviral properties. Fucoidans extracted from species like *Fucus vesiculosus* and *Undaria pinnatifida* have demonstrated potential therapeutic effects in various preclinical and clinical studies, suggesting their utility in the treatment of cardiovascular diseases, cancer, and viral infections (Usov et al. 2022).

Laminarins: Brown algae synthesize laminarin polysaccharides, β-glucans with immunomodulatory properties that enhance the immune response and stimulate the production of pro-inflammatory cytokines. Laminarins have been investigated for their potential as adjuvants in vaccines and immunotherapies for infectious diseases and cancer (Caseiro et al. 2022).

Green algae (Chlorophyta): Green algae are characterized by their green coloration, resulting from the predominant presence of chlorophyll pigments. They inhabit various aquatic environments, including freshwater lakes, rivers, and marine habitats. Green algae exhibit diverse morphologies, ranging from unicellular organisms to multicellular macroalgae, and contain a wide range of bioactive compounds with pharmaceutical potential (Pierre et al. 2019; Adetunji et al. 2024a).

Bioactive components: Chlorophylls—Green algae are rich sources of chlorophyll pigments, which possess antioxidant properties and contribute to photosynthesis. Chlorophylls have been investigated for their potential therapeutic effects, including detoxification, wound healing, and anticancer activity, although further research is needed to elucidate their mechanisms of action and clinical applications (Martins et al. 2023).

β-Glucans: Green algae produce β-glucan polysaccharides, complex carbohydrates with immunomodulatory properties that enhance the activity of immune cells and stimulate the production of cytokines and antibodies. β-Glucans derived from green algae species like chlorella and spirulina have shown promise as immunotherapeutic agents for enhancing immune function and combating infections and tumors (Zhong et al. 2023).

Pigments: In addition to chlorophylls, green algae produce other pigments, such as lutein, zeaxanthin, and astaxanthin, which possess antioxidant and anti-inflammatory properties. These pigments contribute to the coloration of green algae and may confer various health benefits when consumed as dietary supplements or incorporated into pharmaceutical formulations (Generalić Mekinić et al. 2023).

Generally, seaweeds represent valuable sources of bioactive compounds with diverse pharmacological activities, offering promising avenues for drug discovery and development. The classes of seaweeds—red, brown, and green—each harbour unique bioactive components that hold the potential for addressing a wide range of human health conditions, from infectious diseases to chronic disorders. Continued research into the identification, isolation, and characterization of seaweed-derived bioactives is essential for unlocking their full therapeutic potential and harnessing the benefits of these marine resources for pharmaceutical applications (Lomartire and Gonçalves 2022).

14.4 Extraction and Characterization of Bioactive Compounds from Seaweeds

Seaweeds, also known as marine macroalgae, are abundant sources of bioactive compounds with diverse pharmacological properties. The extraction and characterization of these compounds are crucial steps in harnessing their potential for pharmaceutical applications. This overview discusses the methods used for extracting bioactive compounds from seaweeds and the techniques employed for their characterization (Cotas et al. 2024).

14.5 Extraction Methods

Several extraction techniques are employed to isolate bioactive compounds from seaweeds, including conventional methods and modern approaches utilizing advanced technologies. The choice of extraction method depends on factors such as the type of bioactive compound, seaweed species, desired yield, and purity requirements. Common extraction techniques include (Sosa-Hernández et al. 2018).

Solvent extraction: Solvent extraction involves the use of organic solvents such as ethanol, methanol, acetone, or water to dissolve and extract bioactive compounds from seaweed biomass. This method is widely used for extracting a broad range of compounds, including polysaccharides, polyphenols, lipids, and pigments (Wang et al. 2024).

Supercritical fluid extraction (SFE): SFE utilizes supercritical fluids such as carbon dioxide (CO_2) to extract bioactive compounds from seaweeds under high pressure and temperature conditions. Supercritical CO_2 offers several advantages, including its non-toxic nature, selectivity, and ability to extract heat-sensitive compounds without leaving solvent residues (Uwineza and Waśkiewicz 2020).

Ultrasound-assisted extraction (UAE): UAE utilizes ultrasound waves to disrupt cell walls and enhance the extraction efficiency of bioactive compounds from seaweeds. Ultrasound energy promotes the release of intracellular components into the solvent, resulting in higher extraction yields and reduced extraction times compared to conventional methods (Kumar et al. 2021; Mathew et al. 2024a).

Microwave-assisted extraction (MAE): MAE employs microwave radiation to accelerate the extraction of bioactive compounds from seaweeds by promoting heat transfer and mass transfer processes. Microwave energy penetrates the seaweed matrix, causing rapid heating and vaporization of solvent molecules, leading to enhanced extraction efficiency (Quitério et al. 2022).

Enzyme-assisted extraction (EAE): EAE involves the use of enzymes such as carbohydrases, proteases, or lipases to hydrolyze cell wall components and release bioactive compounds from seaweed biomass. Enzymes can improve extraction yields and facilitate the recovery of specific compounds by targeting specific bonds or structural components (Lemes et al. 2022).

14.6 Characterization Techniques

Once bioactive compounds are extracted from seaweeds, they undergo characterization to identify their chemical composition, structural properties, and biological activities. Characterization techniques provide valuable insights into the nature and functionality of seaweed-derived bioactives, guiding further research and development efforts (Inobeme et al. 2023b). Common characterization techniques include:

HPLC (high-performance liquid chromatography): HPLC is a powerful analytical technique used to separate, identify, and quantify individual components within complex mixtures of bioactive compounds. HPLC systems employ a mobile phase, stationary phase, and detector to elute and detect compounds based on their retention times and absorbance properties (Kumar 2017).

GC-MS (gas chromatography-mass spectrometry): GC-MS combines gas chromatography with mass spectrometry to analyze volatile and semi-volatile compounds present in seaweed extracts. GC separates compounds based on their volatility, while MS identifies and quantifies compounds based on their mass-to-charge ratios and fragmentation patterns (Yamamoto et al. 2014; Adetunji et al. 2024b).

FTIR (Fourier transform infrared spectroscopy): FTIR spectroscopy measures the absorption and transmission of infrared light by functional groups present in bioactive compounds, providing information about their chemical structure and composition. FTIR spectra can be used to identify specific bonds and characterize molecular structures (Damto et al. 2023).

NMR (nuclear magnetic resonance spectroscopy): NMR spectroscopy analyzes the nuclear magnetic properties of atoms within bioactive compounds, yielding information about their molecular structure, conformation, and dynamics. NMR spectra provide valuable data on chemical shifts, coupling constants, and connectivity within molecules.

Mass spectrometry (MS): MS analyzes the mass-to-charge ratios of ions generated from bioactive compounds, allowing for their identification, quantification, and structural elucidation. MS techniques such as MALDI-TOF (Matrix-Assisted Laser Desorption/Ionization Time-of-Flight) and ESI (Electrospray Ionization) are commonly used for analyzing seaweed-derived compounds (Pintér et al. 2021).

The extraction and characterization of bioactive compounds from seaweeds represent essential steps in harnessing their pharmaceutical potential. Various extraction methods, including solvent extraction, supercritical fluid extraction, ultrasound-assisted extraction, microwave-assisted extraction, and enzyme-assisted extraction, are employed to isolate bioactives from seaweed biomass. Subsequently, characterization techniques such as HPLC, GC-MS, FTIR, NMR, and mass spectrometry provide insights into the chemical composition, structure, and functional properties of seaweed-derived compounds. By combining extraction and characterization approaches, researchers can identify novel bioactive compounds with diverse pharmacological activities, paving the way for the development of new drugs and therapeutic agents derived from seaweeds (Cikoš et al. 2018; Mathew et al. 2024b).

14.7 Applications of Bioactive Compounds from Sea Weeds in the Pharmaceutical Industry

Table 14.1 provides an overview of various bioactive compounds derived from different classes of seaweeds and their potential pharmaceutical applications. You can find specific examples of seaweed species for each category based on research findings and known bioactive properties.

Table 14.1 Applications of bioactive compounds from seaweeds in the pharmaceutical industry

Bioactive compounds	Pharmaceutical application	Seaweed source	Examples of species	References
Polysaccharides	Antiviral agents Anti-inflammatory drugs Anticoagulants Wound healing agents Tissue engineering scaffolds	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	*Chondrus crispus* *Fucus vesiculosus* *Ulva lactuca*	de Jesus Raposo et al. (2015), Mathew et al. (2024c)
Polyphenols	Antioxidant Anti-inflammatory drugs Anticancer agents Neuroprotective agents Cardioprotective agents	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	*Ecklonia cava* *Sargassum* spp. *Chlorella vulgaris*	Besednova et al. (2021) Inobeme et al. (2024b)
Peptides	Antimicrobial agents Antihypertensive drugs Immunomodulators Anticancer agents Neuroactive peptides	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta	*Porphyra* spp. *Ascophyllum nodosum* *Spirulina platensis*	Afzal et al. (2023)
Pigments	Photoprotective agents Antioxidants Anti-inflammatory agents Probiotic supplements	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	*Palmaria palmata* *Laminaria digitata* *Dunaliella salina*	Gomez-Zavaglia et al. (2019), Adetunji et al. (2024a)
Lipids	Anti-inflammatory drugs Neuroprotective agents Cardioprotective agents Anticancer agent Emulsifiers	Red algae (Rhodophyta) Brown algae (Phaeophyceae) Green algae (Chlorophyta)	*Gracilaria* spp. *Macrocystis pyrifera* *Codium fragile*	Jaworowska and Murtaza (2022)

Seaweeds, also known as marine macroalgae, are rich sources of bioactive compounds with diverse pharmacological properties. These compounds have attracted significant interest from the pharmaceutical industry due to their potential therapeutic benefits. Following are some key applications of bioactive compounds derived from seaweeds in pharmaceutical research and development. Bioactive compounds extracted from seaweeds, particularly polysaccharides such as carrageenans and fucoidans, have demonstrated potent antiviral activity against a range of viruses, including herpes simplex virus (HSV), human immunodeficiency virus (HIV), and influenza virus. These compounds inhibit viral replication and attachment to host cells, making them promising candidates for the development of antiviral drugs (Øverland et al. 2019).

Polyphenols and polysaccharides from seaweeds exhibit significant anti-inflammatory properties by modulating immune responses and reducing the production of pro-inflammatory mediators. These bioactive compounds have potential applications in the treatment of inflammatory disorders such as arthritis, asthma, and inflammatory bowel disease. Sulfated polysaccharides extracted from seaweeds, such as heparin-like compounds found in red and green algae, possess anticoagulant and antithrombotic activities. These compounds inhibit blood clotting by interfering with the coagulation cascade and platelet aggregation, offering therapeutic potential for the prevention and treatment of thrombotic disorders (Khursheed et al. 2023).

Phenolic compounds, pigments, and peptides derived from seaweeds exhibit potent antioxidant properties by scavenging free radicals and reducing oxidative stress. These bioactive compounds protect cells and tissues from oxidative damage and may help prevent age-related diseases such as cardiovascular disease, neurodegenerative disorders, and cancer. Peptides, polysaccharides, and lipids from seaweeds possess antimicrobial activity against a wide range of bacteria, fungi, and viruses. These bioactive compounds disrupt microbial cell membranes, inhibit enzyme activity, and interfere with microbial growth and replication, making them valuable for the development of antimicrobial drugs and topical treatments for infectious diseases (Michalak et al. 2022).

Polysaccharides, peptides, and growth factors derived from seaweeds promote wound healing and tissue regeneration by stimulating cell proliferation, angiogenesis, and collagen synthesis. These bioactive compounds accelerate the repair of damaged tissues and enhance the closure of wounds, making them useful for the development of wound dressings and therapeutic agents for chronic wounds and burns. Polyphenols, peptides, and lipids from seaweeds exhibit neuroprotective properties by reducing oxidative stress, inflammation, and neuronal damage in the brain and nervous system. These bioactive compounds may have potential applications in the prevention and treatment of neurodegenerative disorders such as Alzheimer's disease, Parkinson's disease, and stroke. Polysaccharides, polyphenols, and lipids from seaweeds have cardio-protective effects by reducing blood pressure, cholesterol levels, and inflammation, and improving vascular function and endothelial health. These bioactive compounds may help prevent cardiovascular

diseases such as hypertension, atherosclerosis, and coronary artery disease (Keykhaee et al. 2023).

14.8 Recent Report on Application of Bioactive Compounds from Seaweeds in Pharmaceutical Industries

Seaweeds, or marine macroalgae, have gained increasing attention in the pharmaceutical industry due to their rich bioactive compound content and diverse pharmacological properties. Recent research has focused on exploring the potential of seaweed-derived compounds as novel therapeutics for various human health conditions. This report provides an overview of recent developments and advancements in the application of bioactive compounds from seaweeds in pharmaceutical industries (Lomartire and Gonçalves 2022).

Bioactive compounds from seaweeds: Seaweeds are abundant sources of bioactive compounds, including polysaccharides, polyphenols, peptides, pigments, and lipids, which exhibit a wide range of biological activities. Recent studies have elucidated the mechanisms of action and therapeutic potential of these compounds in the treatment and prevention of various diseases (Hentati et al. 2020; Mathew et al. 2024d).

Antiviral agents: One of the most promising applications of seaweed-derived bioactive compounds is in the development of antiviral agents. Research has shown that sulfated polysaccharides from red algae, such as carrageenans and fucoidans, possess potent antiviral activity against enveloped viruses, including herpes simplex virus (HSV), human immunodeficiency virus (HIV), and influenza virus. These compounds inhibit viral entry and replication, making them promising candidates for the development of novel antiviral drugs (Liyanage et al. 2023).

Anti-inflammatory drugs: Polyphenols and polysaccharides from seaweeds have demonstrated significant anti-inflammatory properties by modulating immune responses and reducing the production of pro-inflammatory mediators. Recent studies have highlighted the potential of these compounds in the treatment of inflammatory disorders such as arthritis, asthma, and inflammatory bowel disease. Furthermore, seaweed-derived peptides have shown promise as anti-inflammatory agents by inhibiting the activity of inflammatory enzymes and cytokines (Liyanage et al. 2023).

Anticoagulants and cardiovascular drugs: Sulfated polysaccharides from seaweeds, including heparin-like compounds found in red and green algae, exhibit anticoagulant and antithrombotic activities. These compounds have potential applications in the prevention and treatment of thrombotic disorders such as deep vein thrombosis (DVT) and pulmonary embolism (PE). Additionally, polyphenols and lipids from seaweeds have cardio-protective effects by reducing blood pressure, cholesterol levels, and inflammation, thereby lowering the risk of cardiovascular diseases such as hypertension and atherosclerosis (Kuznetsova et al. 2021; Olorunsola et al. 2024).

Antioxidants and neuroprotective agents: Seaweed-derived polyphenols, pigments, and peptides possess potent antioxidant properties, scavenging free radicals and reducing oxidative stress in cells and tissues. Recent research has focused on the neuroprotective effects of these compounds in the prevention and treatment of neurodegenerative disorders such as Alzheimer's disease and Parkinson's disease. Furthermore, lipids from seaweeds have shown neuroprotective effects by enhancing neuronal survival and function (Lomartire and Gonçalves 2023).

Antimicrobial agents: Bioactive compounds from seaweeds, including polysaccharides, peptides, and lipids, exhibit antimicrobial activity against a wide range of bacteria, fungi, and viruses. Recent studies have investigated the potential of these compounds as alternatives to conventional antibiotics for the treatment of antibiotic-resistant infections. Furthermore, seaweed-derived peptides have shown promise as novel antimicrobial agents with broad-spectrum activity against pathogenic microorganisms (Lomartire and Gonçalves 2023).

14.9 Conclusion

The recent report underscores the significant potential of bioactive compounds derived from seaweeds in revolutionizing the pharmaceutical industry. Seaweeds, with their rich diversity of polysaccharides, polyphenols, peptides, pigments, and lipids, offer a vast reservoir of compounds with diverse pharmacological activities. The applications of these bioactives span various therapeutic areas, including antiviral, anti-inflammatory, anticoagulant, cardiovascular, antioxidant, neuroprotective, and antimicrobial agents. Recent advancements in research have elucidated the mechanisms of action of seaweed-derived compounds and their therapeutic potential in addressing a wide range of human health conditions. From combating viral infections and inflammatory disorders to preventing cardiovascular diseases and neurodegenerative disorders, seaweed-derived bioactives offer promising solutions to some of the most pressing healthcare challenges of our time. Moreover, the sustainable and eco-friendly nature of seaweed cultivation makes it an attractive source of bioactive compounds for pharmaceutical applications. Seaweeds grow rapidly and require minimal resources, making them a renewable and environmentally responsible source of raw materials for drug discovery and development.

References

Adetunji CO, Michael OS, Shariati MA, Estella OU, Osemwegie OO, Olaniyan O, Oyedara OO, Rebezov M, Ajayi OO, Ibadullayeva G, Inobeme A, Mathew JT, Adetunji JB, Ugwu NP, Bodunrinde RE, Adeniyi MJ (2024a) Citrullus lanatus (Thunberg) Matsumura and Nakai: Nanofungicidal and other biological activities. In: Handbook of agricultural biotechnology, vol 1. Wiley, pp 187–213. https://doi.org/10.1002/9781119836544.ch11

Adetunji CO, Mathew JT, Inobeme A, Taiwo O, Olaniyan O, Shakira G, Wadazani D (2024b) Application of biosensors for detection and monitoring of water quality. In: Organic and inorganic materials based sensors. Wiley, pp 1065–1077. https://doi.org/10.1002/9783527834266.ch46

Adetuyi BO, Mathew JT, Inobeme A, Falana YO, Adetunji CO, Shahnawaz M, Oyewole OA, Eniola KIT, Yerima MB (2024) Sources, uses and transport of secondary microplastics from land to marine environment. In: Microplastic pollution, vol 1. Springer, Singapore, pp 35–49. https://doi.org/10.1007/978-981-99-8357-5_3

Afzal S, Yadav AK, Poonia AK, Choure K, Yadav AN, Pandey A (2023) Antimicrobial therapeutics isolated from algal source: retrospect and prospect. Biologia 78(2):291–305. https://doi.org/10.1007/s11756-022-01207-3

Banach JL, Koch SJI, Hoffmans Y, van den Burg SWK (2022) Seaweed value chain stakeholder perspectives for food and environmental safety hazards. Foods (Basel, Switzerland) 11(10):1514. https://doi.org/10.3390/foods11101514

Besednova NN, Andryukov BG, Zaporozhets TS, Kryzhanovsky SP, Fedyanina LN, Kuznetsova TA, Zvyagintseva TN, Shchelkanov MY (2021) Antiviral effects of polyphenols from marine algae. Biomedicines 9(2):200. https://doi.org/10.3390/biomedicines9020200

Caseiro C, Dias JNR, de Andrade Fontes CMG, Bule P (2022) From cancer therapy to winemaking: the molecular structure and applications of β-glucans and β-1, 3-Glucanases. Int J Mol Sci 23(6):3156. https://doi.org/10.3390/ijms23063156

Chen H, Chu JS, Chen J, Luo Q, Wang H, Lu R, Zhu Z, Yuan G, Yi X, Mao Y, Lu C, Wang Z, Gu D, Jin Z, Zhang C, Weng Z, Li S, Yan X, Yang R (2022) Insights into the ancient adaptation to intertidal environments by red algae based on a genomic and multiomics investigation of Neoporphyra haitanensis. Mol Biol Evol 39(1):msab315. https://doi.org/10.1093/molbev/msab315

Cikoš AM, Jokić S, Šubarić D, Jerković I (2018) Overview on the application of modern methods for the extraction of bioactive compounds from marine macroalgae. Mar Drugs 16(10):348. https://doi.org/10.3390/md16100348

Cotas J, Lomartire S, Gonçalves AMM, Pereira L (2024) From ocean to medicine: harnessing Seaweed's potential for drug development. Int J Mol Sci 25(2):797. https://doi.org/10.3390/ijms25020797

Damto T, Zewdu A, Birhanu T (2023) Application of Fourier transform infrared (FT-IR) spectroscopy and multivariate analysis for detection of adulteration in honey markets in Ethiopia. Curr Res Food Sci 7:100565. https://doi.org/10.1016/j.crfs.2023.100565

de Jesus Raposo MF, de Morais AM, de Morais RM (2015) Marine polysaccharides from algae with potential biomedical applications. Mar Drugs 13(5):2967–3028. https://doi.org/10.3390/md13052967

Elbandy M (2022) Anti-inflammatory effects of marine bioactive compounds and their potential as functional food ingredients in the prevention and treatment of Neuroinflammatory disorders. Molecules (Basel, Switzerland) 28(1):2. https://doi.org/10.3390/molecules28010002

El-Beltagi HS, Mohamed AA, Mohamed HI, Ramadan KMA, Barqawi AA, Mansour AT (2022) Phytochemical and potential properties of seaweeds and their recent applications: a review. Mar Drugs 20(6):342. https://doi.org/10.3390/md20060342

Generalić Mekinić I, Šimat V, Rathod NB, Hamed I, Čagalj M (2023) Algal carotenoids: chemistry, sources, and application. Foods (Basel, Switzerland) 12(14):2768. https://doi.org/10.3390/foods12142768

Gomez-Zavaglia A, Prieto Lage MA, Jimenez-Lopez C, Mejuto JC, Simal-Gandara J (2019) The potential of seaweeds as a source of functional ingredients of prebiotic and antioxidant value. Antioxidants (Basel, Switzerland) 8(9):406. https://doi.org/10.3390/antiox8090406

Hans N, Malik A, Naik S (2021) Antiviral activity of sulfated polysaccharides from marine algae and its application in combating COVID-19: mini review. Bioresour Technol Rep 13:100623. https://doi.org/10.1016/j.biteb.2020.100623

Hentati F, Tounsi L, Djomdi D, Pierre G, Delattre C, Ursu AV, Fendri I, Abdelkafi S, Michaud P (2020) Bioactive polysaccharides from seaweeds. Molecules (Basel, Switzerland) 25(14):3152. https://doi.org/10.3390/molecules25143152

Inobeme A, Adetunji CO, Mathew JT, Ajai AI, Inobeme J, Bamigboye MO, Onyeaku S, Maliki M, Eziukwu C, Tawa K (2023a) Nanotechnology for bioremediation of heavy metals. In: Microbial

technologies in industrial wastewater treatment. Springer Nature, Singapore, pp 19–30. https://doi.org/10.1007/978-981-99-2435-6_2

Inobeme A, Adetunji CO, Mathew JT, Ajai AI, Mann A, Inobeme J, Oyedolapo B, Adekoya MA, Onyeaku S (2023b) Diversity, biodegradation and bioremediation of polycyclic aromatic hydrocarbons. In: Microbial technologies in industrial wastewater treatment. Springer Nature, Singapore, pp 31–50. https://doi.org/10.1007/978-981-99-2435-6_3

Inobeme A, Shahnawaz M, Adetunji CO, Mathew JT, Adetuyi BO, Popoola OA, Olaitan FY, Akinbo O, Kolawole OM, Oyewole OA, KIT E (2024a) Primary microplastic: source, uses, transportation from land to marine environment. In: Microplastic pollution, vol 1. Springer, Singapore, pp 23–33. https://doi.org/10.1007/978-981-99-8357-5_2

Inobeme A, Adetunji CO, Mathew JT, Ajai IA, Jacob JO (2024b) Characterization of plant-based Nanobiofungicides. In: Handbook of agricultural biotechnology. Wiley, pp 81–97. https://doi.org/10.1002/9781119836544.ch5

Jaworowska A, Murtaza A (2022) Seaweed derived lipids are a potential anti-inflammatory agent: a review. Int J Environ Res Public Health 20(1):730. https://doi.org/10.3390/ijerph20010730

Keykhaee M, Sorouri F, Rahimifard M, Baeeri M, Forumadi A, Firoozpour L, Khoobi M (2023) Polysaccharide-based hydrogel enriched by epidermal growth factor peptide fragment for improving the wound healing process. Heliyon 9(12):e22749. https://doi.org/10.1016/j.heliyon.2023.e22749

Khursheed M, Ghelani H, Jan RK, Adrian TE (2023) Anti-inflammatory effects of bioactive compounds from seaweeds, bryozoans, jellyfish, shellfish and peanut worms. Mar Drugs 21(10):524. https://doi.org/10.3390/md21100524

Kumar BR (2017) Application of HPLC and ESI-MS techniques in the analysis of phenolic acids and flavonoids from green leafy vegetables (GLVs). J Pharm Anal 7(6):349–364. https://doi.org/10.1016/j.jpha.2017.06.005

Kumar K, Srivastav S, Sharanagat VS (2021) Ultrasound assisted extraction (UAE) of bioactive compounds from fruit and vegetable processing by-products: a review. Ultrason Sonochem 70:105325. https://doi.org/10.1016/j.ultsonch.2020.105325

Kuznetsova TA, Andryukov BG, Makarenkova ID, Zaporozhets TS, Besednova NN, Fedyanina LN, Kryzhanovsky SP, Shchelkanov MY (2021) The potency of seaweed sulfated polysaccharides for the correction of hemostasis disorders in COVID-19. Molecules (Basel, Switzerland) 26(9):2618. https://doi.org/10.3390/molecules26092618

Lemes AC, Egea MB, de Oliveira Filho JG, Gautério GV, Ribeiro BD, Coelho MAZ (2022) Biological approaches for extraction of bioactive compounds from agro-industrial by-products: a review. Front Bioeng Biotechnol 9:802543. https://doi.org/10.3389/fbioe.2021.802543

Liyanage NM, Nagahawatta DP, Jayawardena TU, Sanjeewa KKA, Jayawrdhana HHACK, Kim JI, Jeon YJ (2023) Sulfated polysaccharides from seaweeds: a promising strategy for combatting viral diseases-a review. Mar Drugs 21(9):461. https://doi.org/10.3390/md21090461

Lomartire S, Gonçalves AMM (2022) An overview of potential seaweed-derived bioactive compounds for pharmaceutical applications. Mar Drugs 20(2):141. https://doi.org/10.3390/md20020141

Lomartire S, Gonçalves AMM (2023) Marine macroalgae polyphenols as potential neuroprotective antioxidants in neurodegenerative diseases. Mar Drugs 21(5):261. https://doi.org/10.3390/md21050261

Martins T, Barros AN, Rosa E, Antunes L (2023) Enhancing health benefits through chlorophylls and chlorophyll-rich agro-food: a comprehensive review. Molecules (Basel, Switzerland) 28(14):5344. https://doi.org/10.3390/molecules28145344

Mathew JT, Inobeme A, Adetuyi BO, Falana YO, Adetunji CO, Shahnawaz M (2024a) Application of microplastics in toiletry products. In: Shahnawaz M, Adetunji CO, Dar MA, Zhu D (eds) Microplastic pollution. Springer, Singapore, pp 73–84. https://doi.org/10.1007/978-981-99-8357-5_5

Mathew JT, Inobeme A, Adetuyi BO, Adetunji CO, Popoola OA, Olaitan FY, Akinbo O, Shahnawaz M, Oyewole OA, Eniola KIT, Yerima BM (2024b) General introduction of microplastic: uses,

types, and generation. In: Microplastic pollution, vol 1. Springer, Singapore, pp 3–21. https://doi.org/10.1007/978-981-99-8357-5_1

Mathew JT, Inobeme A, Adekoya MA, Musah M, Azeh Y, Otori AA, Shaba EY, Mamman A (2024c) Processing techniques, test methods, and regulatory standards of smart textiles. In: Smart textiles from natural resources, vol 1. Elsevier Inc, pp 237–272. https://doi.org/10.1016/B978-0-443-15471-3.00016-9

Mathew JT, Inobeme A, Abdulkadir A, Etsuyankpa MB, Shaba EY, Musah M, Azeh Y, Adetunji CO, Ibrahim AM, Tanko E, Mamman A (2024d) Properties and characteristics of nanocoatings for medicinal applications. In: Sustainable approach to protective nanocoatings. IGI Global; Tomorrow's Research Today, pp 203–227. https://doi.org/10.4018/979-8-3693-3136-1.ch007

Menaa F, Wijesinghe PAUI, Thiripuranathar G, Uzair B, Iqbal H, Khan BA, Menaa B (2020) Ecological and industrial implications of dynamic seaweed-associated microbiota interactions. Mar Drugs 18(12):641. https://doi.org/10.3390/md18120641

Menaa F, Wijesinghe U, Thiripuranathar G, Althobaiti NA, Albalawi AE, Khan BA, Menaa B (2021) Marine algae-derived bioactive compounds: a new wave of nanodrugs? Mar Drugs 19(9):484. https://doi.org/10.3390/md19090484

Michalak I, Tiwari R, Dhawan M, Alagawany M, Farag MR, Sharun K, Emran TB, Dhama K (2022) Antioxidant effects of seaweeds and their active compounds on animal health and production – a review. Vet Q 42(1):48–67. https://doi.org/10.1080/01652176.2022.2061744

Mohibbullah M, Haque MN, Sohag AAM, Hossain MT, Zahan MS, Uddin MJ, Hannan MA, Moon IS, Choi JS (2022) A systematic review on marine algae-derived Fucoxanthin: an update of pharmacological insights. Mar Drugs 20(5):279. https://doi.org/10.3390/md20050279

Olorunsola A, Adetunji CO, Olaniyan O, Adetunji JB, Akinbo K, Adetuyi BO, Inobeme A, Mathew JT, Ajenifujah-Solebo SO (2024) Application of nanotechnology for the production of biopesticides, bioinsecticides, bioherbicides, mosquitoe repellants and biofungicides. In: Handbook of agricultural biotechnology. Wiley, pp 293–309. https://doi.org/10.1002/9781119836483.ch11

Øverland M, Mydland LT, Skrede A (2019) Marine macroalgae as sources of protein and bioactive compounds in feed for monogastric animals. J Sci Food Agric 99(1):13–24. https://doi.org/10.1002/jsfa.9143

Pereira L, Cotas J (2023) Therapeutic potential of polyphenols and other micronutrients of marine origin. Mar Drugs 21(6):323. https://doi.org/10.3390/md21060323

Pereira L, Cotas J, Gonçalves AM (2024) Seaweed proteins: a step towards sustainability? Nutrients 16(8):1123. https://doi.org/10.3390/nu16081123

Pierre G, Delattre C, Dubessay P, Jubeau S, Vialleix C, Cadoret JP, Probert I, Michaud P (2019) What is in store for EPS microalgae in the next decade? Molecules (Basel, Switzerland) 24(23):4296. https://doi.org/10.3390/molecules24234296

Pintér G, Hohmann KF, Grün JT, Wirmer-Bartoschek J, Glaubitz C, Fürtig B, Schwalbe H (2021) Real-time nuclear magnetic resonance spectroscopy in the study of biomolecular kinetics and dynamics. Mag Reson (Gottingen, Germany) 2(1):291–320. https://doi.org/10.5194/mr-2-291-2021

Quitério E, Grosso C, Ferraz R, Delerue-Matos C, Soares C (2022) A critical comparison of the advanced extraction techniques applied to obtain health-promoting compounds from seaweeds. Mar Drugs 20(11):677. https://doi.org/10.3390/md20110677

Sosa-Hernández JE, Escobedo-Avellaneda Z, Iqbal HMN, Welti-Chanes J (2018) State-of-the-art extraction methodologies for bioactive compounds from algal biome to meet bio-economy challenges and opportunities. Molecules (Basel, Switzerland) 23(11):2953. https://doi.org/10.3390/molecules23112953

Takao S, Kumagai NH, Yamano H, Fujii M, Yamanaka Y (2015) Projecting the impacts of rising seawater temperatures on the distribution of seaweeds around Japan under multiple climate change scenarios. Ecol Evol 5(1):213–223. https://doi.org/10.1002/ece3.1358

Usov AI, Bilan MI, Ustyuzhanina NE, Nifantiev NE (2022) Fucoidans of Brown algae: comparison of sulfated polysaccharides from Fucus vesiculosus and Ascophyllum nodosum. Mar Drugs 20(10):638. https://doi.org/10.3390/md20100638

Uwineza PA, Waśkiewicz A (2020) Recent advances in supercritical fluid extraction of natural bioactive compounds from natural plant materials. Molecules (Basel, Switzerland) 25(17):3847. https://doi.org/10.3390/molecules25173847

Wang T, Zhu L, Mei L, Kanda H (2024) Extraction and separation of natural products from microalgae and other natural sources using liquefied dimethyl ether, a green solvent: a review. Foods (Basel, Switzerland) 13(2):352. https://doi.org/10.3390/foods13020352

Yamamoto M, Baldermann S, Yoshikawa K, Fujita A, Mase N, Watanabe N (2014) Determination of volatile compounds in four commercial samples of Japanese green algae using solid phase microextraction gas chromatography mass spectrometry. Sci World J 2014:289780. https://doi.org/10.1155/2014/289780

Zhong X, Wang G, Li F, Fang S, Zhou S, Ishiwata A, Tonevitsky AG, Shkurnikov M, Cai H, Ding F (2023) Immunomodulatory effect and biological significance of β-glucans. Pharmaceutics 15(6):1615. https://doi.org/10.3390/pharmaceutics15061615