Seaweeds as Silent Healers

Seaweeds as Silent Healers:

Insight into the Pharmacological Potential of Marine Algal Metabolites

Edited by

Thilina L. Gunathilaka
and Hiruni S. Kumarasinghe

Cambridge Scholars Publishing

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We are profoundly grateful to Cambridge Scholars Publishing Press, UK, for their commitment to bringing this work to fruition. I wish to extend my deepest thanks to all contributing authors for their invaluable chapters and significant research efforts.

PREFACE

The marine environment represents a vast and largely untapped reservoir of bioactive compounds, with seaweeds emerging as a significant source of pharmacologically potent metabolites. This book, "Seaweeds as Silent Healers: Mechanistic Insight into the Pharmacological Potential of Marine Algal Metabolites," aims to elucidate the therapeutic potential and underlying mechanisms of action of bioactive compounds derived from marine algae.

The primary objective of this volume is to provide a detailed compendium of the diverse bioactive metabolites found in seaweeds, emphasizing their molecular mechanisms and pharmacological applications. This resource is intended for researchers, scientists, and healthcare professionals engaged in marine biotechnology, natural product chemistry, and pharmacology.

Over recent decades, advancements in marine natural product research have uncovered numerous bioactive compounds with significant therapeutic potential. This book consolidates current research findings, methodological advancements, and innovative approaches in the isolation and characterization of these compounds. By exploring the pharmacodynamic properties of seaweed-derived metabolites, this volume seeks to highlight their relevance in drug discovery and development.

The realization of this book has been facilitated by the collaborative efforts of esteemed researchers and experts in the field. Their contributions have been pivotal in ensuring the scientific rigor and comprehensive coverage of the subject matter.

We extend our profound gratitude to all the contributors and reviewers whose expertise and insights have greatly enriched this book. Their meticulous feedback and scholarly input have been invaluable. We are also immensely grateful to Cambridge Scholars Publishing Press, UK, for their steadfast support and facilitation of this project.

Dr. Thilina L. Gunathilaka & Hiruni S. Kumarasinghe
Editors

Chapter 1

Introduction to Marine Seaweeds

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Abstract

This chapter provides a comprehensive overview of seaweeds, delving into their remarkable diversity and significance. Marine macroalgae or seaweeds play a pivotal role in maintaining oceanic health, being primary contributors to oxygen production, primary producers in aquatic food webs, and key players in climate regulation. Through this paper, the various categories of marine macroalgae, namely green, brown, and red algae, are explored, revealing their distinctive features and ecological importance. Additionally, the paper highlights their commercial and industrial applications, including their role in food production, pharmaceuticals, and cosmeceutical, underscoring their substantial economic value. Furthermore, it emphasizes the pharmaceutical significance of marine macroalgae in advance, shedding light on their potential contributions to medical advancements. In summation, this chapter offers an insightful introduction to marine algae, unveiling their fascinating world and underscoring their crucial role in the field of pharmaceutical research.

Keywords - Bioactive constituents, Chlorophyta, Phaeophyta, Pharmaceutical significances Rhodophyta, Seaweed

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1. Introduction

Seaweeds are a diverse group of macroscopic, multicellular algae found in abundance in the world's oceans. Traditionally, they have been utilized for various purposes, such as food, agriculture, and cosmetics. However, recent research has unveiled the hidden treasure trove of bioactive compounds that seaweeds produce. These compounds, collectively referred to as marine algal metabolites, have shown immense promise in various pharmaceutical and therapeutic applications [1].

Seaweeds are a rich source of bioactive metabolites, including polysaccharides, polyphenols, peptides, and other organic molecules. These compounds have demonstrated various pharmacological activities, such as anti-inflammatory, antioxidant, antiviral, and anticancer properties [2]. Seaweeds' bioactive components have the potential to become the basis for the development of novel drugs and therapies, which can address a wide range of health issues. Many marine seaweed species are known for their anti-inflammatory properties [3]. Compounds like fucoidans, found in brown seaweeds, have exhibited significant anti-inflammatory effects. These compounds can be invaluable in treating chronic inflammatory conditions like arthritis, and they hold the potential to reduce the reliance on conventional anti-inflammatory drugs, which may have adverse side effects. Oxidative stress is implicated in a variety of diseases, including cardiovascular conditions, neurodegenerative disorders, and cancer. Marine seaweeds are rich in antioxidants like phlorotannins, fucoxanthin, fucoidan, carrageenan, agar, phenols, ulvan, and caulerpin, which can scavenge harmful free radicals and protect cells from damage [4]. By incorporating seaweed-derived antioxidants into pharmaceuticals or dietary supplements, researchers can harness these natural defenses to promote better health. Several marine seaweeds have demonstrated promising anticancer properties. Compounds such as fucoxanthin, found in brown seaweeds, have shown potential in inhibiting the growth of cancer cells and inducing apoptosis. Research into the mechanisms of these compounds is ongoing, offering hope for the development of more effective and less toxic cancer treatments. Marine seaweeds are also being investigated for their antiviral potential. Some studies have explored their role in inhibiting the replication of viruses, including herpes simplex and influenza. This raises the possibility of developing seaweed-based antiviral drugs or supplements to combat viral infections [5].

The importance of marine seaweeds extends beyond their pharmacological potential. Cultivating seaweeds can have positive environmental effects by mitigating carbon dioxide levels in the atmosphere, improving water quality, and providing habitat and food for marine organisms. Sustainable seaweed farming can contribute to both environmental conservation and human health [6].

Seaweeds as Silent Healers meticulously explores these metabolites and their potential to revolutionize modern medicine. The book highlights how marine algae, often overlooked in the world of medicine, possess a treasure trove of bioactive compounds that can be harnessed for therapeutic purposes. It explores the various classes of metabolites found in seaweeds, such as polysaccharides, polyphenols, and peptides and their potential applications in treating a wide range of health issues. Readers will gain a deeper understanding of the mechanisms through which these marine algal metabolites exert their healing effects, including anti-inflammatory, antioxidant, and anti-cancer properties. The book also discusses the extraction and purification of these compounds and their role in drug development, providing valuable insights for researchers and pharmaceutical industries [7].

1.1 Classification of Marine Seaweeds Based on Color: Red, Green, and Brown Seaweeds

Seaweeds, also known as macroalgae, are a diverse group of multicellular, photosynthetic marine organisms that belong to the larger taxonomic group known as algae. These remarkable organisms have a significant ecological and economic impact, serving as critical primary producers in aquatic ecosystems, providing habitat and sustenance for a variety of marine life, and even finding applications in human nutrition, medicine, and industry. Their classification is primarily based on color, with the three main groups being red seaweeds (Rhodophyta), green seaweeds (Chlorophyta), and brown seaweeds (Phaeophyceae) [8] (Figure 1) (Table 1).

Red seaweeds are characterized by their red to purplish coloration, which results from the presence of the pigment phycoerythrin. They inhabit a wide range of marine environments, from intertidal zones to deep-sea habitats. Key characteristics of red seaweeds include their complex life cycles with alternation of generations, the absence of flagellated cells, and the presence of a distinct cell wall component called agar. Agar, a valuable substance used in the food and pharmaceutical industries, is extracted from certain species of red seaweeds. Notable examples of red seaweeds include dulse (*Palmaria palmata*), nori (*Porphyra spp*.), and carrageen moss (Chondrus crispus) [9], [10].

Green seaweeds are characterized by their green coloration due to the dominance of chlorophyll, the same pigment found in land plants. They often inhabit shallow waters and are more common in freshwater environments than their red and brown counterparts. Green seaweeds exhibit a simple life cycle with no alternation of generations, have flagellated reproductive cells (zoospores), and lack complex structures like true roots. Unlike red seaweeds, green seaweeds do not produce agar but has been a source of other valuable products like ulvan and bioactive compounds. Notable examples of green seaweeds include sea lettuce (Ulva spp.), green sea fingers (Codium spp.), and the commercially important gutweed (Ulva intestinalis) [11].

Brown seaweeds are distinguished by their brown to dark olive coloration, primarily due to the presence of the pigment fucoxanthin. They are commonly found in temperate and cold-water environments and tend to be larger and more structurally complex than red and green seaweeds. Brown seaweeds have a life cycle with alternation of generations, similar to red seaweeds, and possess flagellated reproductive cells (spores). Unlike the other two groups, brown seaweeds are a source of alginates, which are widely used in the food, pharmaceutical, and cosmetic industries due to their gelling and thickening properties. Notable examples of brown seaweeds include kelp (Laminaria spp.), bladderwrack (Fucus spp.), and rockweed (Ascophyllum nodosum) [10].

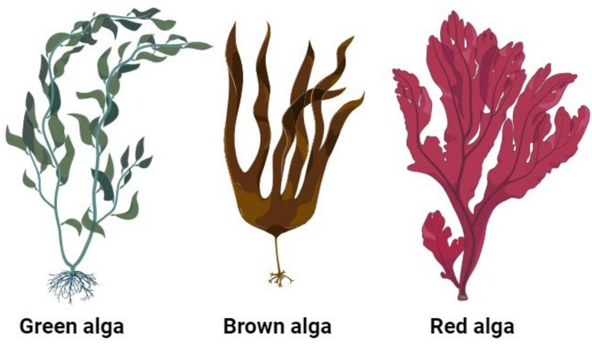

Fig 1-1: Classification of Marine Seaweeds Based on Colour

Name of the alga	*Algal group*	*Clinical significances*	*References*
Ulva fasciata	Green alga	Anti-bacterial, antioxidant effects	[12]
Ulva reticulata	Green alga	Anti-bacterial, antioxidant effects	[13]
Ulva compressa	Brown alga	Anti-bacterial, antioxidant effects	[14]
Sargassum plagiophyllum	Brown alga	Anti-bacterial, antioxidant effects	[15]
Chlorococcum sp.	Green alga	Anti-bacterial, antioxidant effects	[16]
S. muticulum	Brown alga	Antibacterial, antifungal, anti-angiogenesis effects	[17]
Laminaria japonica	Green alga	Anti-coagulant, anti-bacterial and antifouling effects	[18]
Sargassum myriocystum,	Green alga	Anti-coagulant, anti-bacterial and antifouling effects	[19]
Sargassum wightii	Green alga	Anti-coagulant, anti-bacterial and antifouling effects	[19]
Gelidium pusillum	Green alga	Anti-coagulant, anti-bacterial and antifouling effects	[20]
Lemanea fluviatilis	Red alga	Anti-coagulant, anti-bacterial and antifouling effects	[21]
Kappaphycus *alvarezii*	Red alga	Anti-coagulant, anti-bacterial and antifouling effects	[22]
Galaxaura elongate	Red alga	Anti-coagulant, anti-bacterial and antifouling effects	[23]
Gracilaria edulis	Red alga	Anti-coagulant, anti-bacterial and antifouling, anti-diabetic, anti-cancer	[24]
Ecklonia maximum	Brown alga	Anti-diabetic effect	[23]
Ecklonia bicyclis	Brown alga	Anti-diabetic effect	[25], [26]
Ecklonia cava	Brown alga	Anti-bacterial effects	[9], [27]
Gracilaria gracilis	Red alga	Anti-cancer effects	[28]
Hypnea musciformis	Red alga	Anti-fungal effects	[29]

Table 1-1: Classification of some marine alga according to their color and their clinical significance

2. Distribution and Habitat

Seaweeds are distributed worldwide, inhabiting a multitude of marine environments. Their global distribution can be broadly categorized as follows:

Intertidal Zones: Seaweeds are often abundant in intertidal areas, where they endure exposure to air during low tide and immersion during high tide. These zones are characterized by high wave action, fluctuating temperature, and variable light conditions. Different species of seaweeds have adapted to specific intertidal niches, such as the upper, middle, and lower intertidal zones [30].

Subtidal Zones: Subtidal regions represent the underwater areas where seaweeds can grow at greater depths. Light availability and water movement vary, affecting the types of seaweeds that can thrive. Kelps, such as giant kelp (Macrocystis), are common in subtidal areas, forming underwater forests [31].

Polar Regions: Seaweeds have adapted to the extreme conditions of polar regions, including the Arctic and Antarctic. These cold-water species are adapted to low temperatures and often exhibit high tolerance to ice cover, with certain species thriving in sea ice habitats [30], [31].

Temperate Zones: Temperate regions, including coastlines with moderate climates, host a diverse assemblage of seaweeds. The flora in these zones can include both cool-water and warm-water species, depending on the local climate [30], [31].

Tropical Zones: In tropical areas, the diversity of seaweed species is often lower compared to temperate regions. The competition for light and nutrients is intense, and many tropical seaweeds exhibit adaptations to high-temperature conditions [30], [31].

2.1 Environmental Factors Influencing Growth and Distribution

Environmental factors play a crucial role in influencing the growth and distribution of seaweeds, which are vital components of marine ecosystems. Seaweeds are highly sensitive to their surroundings, and changes in these environmental conditions can significantly impact their growth and distribution [32].

Temperature plays a critical role in determining the geographical distribution of seaweed species. Different species have adapted to specific temperature ranges. Rising sea temperatures due to climate change can impact the distribution of seaweeds, potentially leading to range shifts and alterations in community composition. Seaweeds have evolved to withstand a range of temperatures. Some species thrive in cold-water environments, such as those found in polar regions, while others are adapted to warmer waters in tropical and subtropical regions. Rising sea temperatures, driven by global climate change, can impact the distribution of seaweeds. As seawater temperatures increase, species may move poleward or to deeper waters to find suitable conditions. This can lead to shifts in their geographical distribution, potentially affecting the structure of marine ecosystems. Seaweeds can be sensitive to temperature extremes, both high and low. Extreme heat can lead to bleaching and reduced growth, while extreme cold can affect metabolic processes and growth rates. Temperature gradients within the water column, known as thermoclines, can influence the vertical distribution of seaweeds. Certain species have adapted to grow at specific depths, where temperature and light conditions are optimal [31], [32].

Light is the primary source of energy for photosynthesis in seaweeds. Light intensity and spectral composition vary with water depth and location. Seaweeds have developed various strategies to adapt to changing light conditions with depth. In shallow, clear waters, light is abundant, and the dominant species often include kelps and other large, light-demanding seaweeds. In deeper waters, light becomes limited, favouring species adapted to lower light conditions. Seaweeds contain different photosynthetic pigments that enable them to capture light efficiently. For instance, the red pigment phycoerythrin is common in deep-water red seaweeds, allowing them to absorb blue and green light effectively. Seasonal variations in daylight length and angle can affect light availability, influencing the growth rates and reproductive cycles of seaweeds [30], [31].

Nutrient availability, particularly nitrogen and phosphorus, significantly influences the growth of seaweeds. Nutrient-rich areas, such as estuaries and upwelling zones, support high seaweed productivity. Excess nutrient input from human activities can lead to eutrophication, which can have detrimental effects on seaweed communities [33].

Wave exposure and water movement can influence the attachment, growth form, and durability of seaweeds. Some species are adapted to high wave energy environments, while others thrive in more sheltered areas. The type of substrate, such as rock, sand, or other seaweeds, can influence the attachment and growth of seaweeds. Some species exhibit strong habitat preferences, colonizing specific substrate types. Salinity levels can vary in different marine environments, including estuaries and coastal areas. Some seaweeds are euryhaline, able to tolerate a wide range of salinities, while others are stenohaline, requiring a specific salinity range for growth. Increased carbon dioxide (CO_2) levels in the atmosphere can lead to ocean acidification, which can affect the ability of seaweeds to calcify and build calcium carbonate structures, impacting their growth and structural integrity [14].

3. Morphology and Anatomy of Marine Seaweeds

Understanding the anatomy of seaweeds is essential for appreciating their ecological roles, adaptations to various habitats, and potential applications in industries like food, cosmetics, and pharmaceuticals. Seaweed anatomy encompasses a range of structures and tissues that enable these organisms to photosynthesize, reproduce, and anchor themselves in dynamic aquatic environments. This exploration delves into the fundamental components of seaweed anatomy, providing insights into their biology and ecological significance [34], [35] (Figure 2).

3.1 Thallus Structure and Morphology:

The primary body of seaweeds is called the thallus, which lacks the organized tissues and structures found in higher plants. Thalli vary greatly in size, shape, and complexity among different seaweed species. In general, thalli consist of three basic parts: the holdfast, stipe, and blades or fronds. The holdfast serves as an anchor, attaching the seaweed to substrates like rocks, other seaweeds, or sand. The stipe functions as a support structure, connecting the holdfast to the blades or fronds. Blades are the leaf-like structures where photosynthesis occurs. They come in various shapes and sizes, reflecting the species' adaptation to different environmental conditions. The morphology of thalli can be highly variable, ranging from the delicate, filamentous structure of green seaweeds to the robust, branched forms of red and brown seaweeds [36].

3.2 Photosynthetic Pigments:

Seaweeds are autotrophic organisms, relying on photosynthesis to produce energy. To capture light efficiently, they contain different photosynthetic pigments, which also contribute to their diverse colours. Chlorophyll-a and chlorophyll-c are common pigments in green seaweeds, providing the characteristic green colour. Red seaweeds contain chlorophyll-a and phycobiliproteins (phycoerythrin and phycocyanin), which give them their reddish and purplish hues. Brown seaweeds, on the other hand, have chlorophyll-a and the accessory pigment fucoxanthin, lending them a brown or olive colour. The presence of these pigments allows seaweeds to photosynthesize efficiently in their respective light environments, whether it be in shallow, clear waters or deeper, low-light conditions [36].

3.3 Reproductive Structures:

Seaweeds have evolved various reproductive structures and strategies to ensure the survival and dispersion of their species. Reproduction in seaweeds can be both sexual and asexual. Sexual reproduction typically involves the formation of specialized structures called conceptacles, which release gametes (reproductive cells) into the water for fertilization. Many seaweeds have separate male and female reproductive structures, while others are hermaphroditic, producing both male and female gametes. Asexual reproduction often occurs through the fragmentation of the thallus, where a broken piece can develop into a new individual. In some seaweeds, asexual reproduction is also achieved through specialized structures, like sporangia or zoospore-producing cells. The diversity of reproductive structures and strategies in seaweeds reflects their ability to adapt to varying environmental conditions [37].

3.4 Structural Adaptations for Survival:

Seaweeds exhibit an array of structural adaptations that contribute to their survival in dynamic marine environments. For example, many seaweeds have flexible thalli that allow them to sway with water motion, reducing the risk of damage from strong waves and currents. Holdfasts often employ a combination of adhesive and mechanical mechanisms to anchor seaweeds firmly to substrates. Some seaweeds have gas-filled bladders or pneumatocysts that help them float and access light in the water column. Others have structural features like spines and irregular frond shapes that deter herbivores. Additionally, certain seaweeds are adapted to grow at specific depths, taking advantage of their ability to photosynthesize in conditions with different light and temperature gradients. These structural adaptations reflect the intricate balance between competition and survival in the dynamic world of marine seaweeds [35], [37].

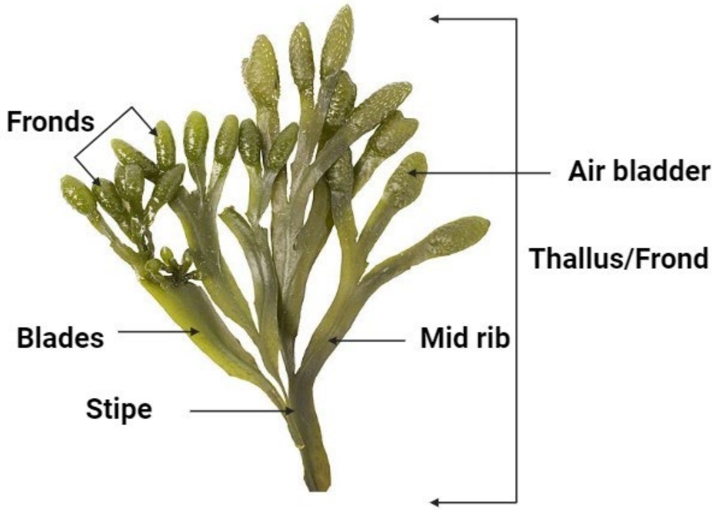

Fig 1-2: Anatomy of seaweeds

4. Life Cycle and Reproduction

Seaweeds exhibit diverse life cycle patterns, often characterized by alternation of generations, a phenomenon where three distinct phases, the haploid (n) (Figure 3), diploid (2n) (Figure 4), haplodiplontic (Figure 5) in their life cycle [38]. These generations are commonly known as the gametophyte and sporophyte phases, each with specific structures and functions. The life cycle patterns of diplohaplontic can be classified into three main types as isomorphic, heteromorphic dioicous, and monoicous. In isomorphic life cycles, the gametophyte and sporophyte generations have similar or nearly identical morphologies. This pattern is typical in some green algae and red algae and is exemplified by species like Ulva and Porphyra. Heteromorphic life cycles involve distinct morphological differences between the gametophyte and sporophyte phases [38], [39]. Brown algae, such as Fucus, exemplify this pattern, where the gametophyte is a small, filamentous structure, while the sporophyte is large and complex. Some algae exhibit dioicous life cycles, meaning they have separate male and female individuals, while others are monoicous, with both male and female reproductive structures on the same individual. The classification can vary among different algal groups. Green algae encompass a diverse group of marine algae with various life cycle patterns. The life cycles of green algae like Ulva and Enteromorpha follows an isomorphic pattern. Their gametophyte and sporophyte phases are morphologically similar and may differ primarily in reproductive structures. In contrast, the life cycles of green algae like Cladophora exhibit a heteromorphic pattern, with distinct differences in size and morphology between the gametophyte and sporophyte generations [39].

Green algae are known for their importance in coastal environments and as valuable resources in industries such as aquaculture and biotechnology. Brown algae, a prominent group of marine algae known for their large and complex structures, exhibit heteromorphic life cycles. Species like Fucus represent a classic example. Their gametophyte phase is a small filament, often found on intertidal rocks, while the sporophyte is a large, brown, blade-like structure, which forms the canopy of underwater forests [40]. Brown algae have significant ecological importance, providing habitat and food for numerous marine organisms. They also have commercial value in industries such as the production of alginates, used as thickeners and emulsifiers in various products. Red algae, including species like Porphyra (nori) and Gracilaria, exhibit isomorphic life cycles, where the gametophyte and sporophyte phases are similar in appearance. In the case of Porphyra, the life cycle involves the alternation between two free-living generations, the conchocelis phase (diploid) and the leafy gametophyte phase (haploid). This unique life cycle is crucial in the cultivation of nori for human consumption. Red algae are also known for their ability to produce carrageenan, a type of sulfated polysaccharide used in the food and pharmaceutical industries [41].

Seaweeds have evolved a range of reproductive structures and mechanisms to ensure the survival and dispersal of their species. Key reproductive structures include conceptacles, receptacles, and sporangia. Conceptacles are specialized structures that house gametes for sexual reproduction. They may contain male and female reproductive structures, which release gametes into the water for fertilization [42]. Receptacles are specific structures found in some red and brown algae, serving as sites for reproductive structures and often releasing spores. Sporangia are structures that produce spores for asexual reproduction. These spores can be dispersed by water currents, promoting the colonization of new habitats. The variety of reproductive structures and mechanisms in marine algae reflects their adaptation to diverse environments and reproductive strategies [42].

The reproductive success of marine algae is influenced by various environmental and physiological factors. Temperature, light availability, nutrient levels, and seasonal cues play essential roles in triggering the onset of reproductive processes. For example, temperature changes can induce the development of reproductive structures in some brown and red algae, while photoperiod and light quality are critical cues for reproductive timing in many green algae. Nutrient availability, particularly nitrogen and phosphorus, affects the growth and reproductive capabilities of seaweeds. Seasonal variations in daylight length and temperature also influence the timing of reproduction in some species. Understanding the interplay between these factors is vital for predicting the reproductive patterns of marine algae and their responses to environmental changes [42].

Marine macroalgae have evolved various adaptations to overcome the challenges of reproduction in the dynamic marine environment. For example, many species have developed mechanisms for efficient spore release, including specialized structures like elastomers and hyaline cells. These adaptations help spores disperse over long distances and increase the likelihood of finding suitable substrates for attachment and growth. Some algae have evolved dioecious or monoecious reproductive strategies to optimize fertilization success. Monoecious species can self-fertilize if mates are scarce, increasing the chances of reproduction. The ability of marine macroalgae to adapt to the often harsh and competitive marine environment is reflected in their diverse reproductive strategies [41], [42].

Reproduction is a crucial process in the life cycle of seaweeds, with significant ecological implications. The dispersal of spores and gametes allows algae to colonize new habitats, contribute to biodiversity, and provide habitat and food for other marine organisms. The seasonal timing of reproduction can influence food webs and nutrient cycling in coastal ecosystems. In addition, the success of algae in competition for space and resources often hinges on their reproductive capabilities. Algal blooms, which can have both beneficial and harmful effects on marine ecosystems, are driven by successful reproduction and the rapid growth of certain algal species. Understanding the ecological significance of algal reproduction is fundamental for managing and conserving coastal and marine environments [39].

Marine macroalgae, like many other marine organisms, face challenges from ongoing environmental changes, including rising sea temperatures, ocean acidification, and nutrient pollution. These changes can influence the timing and success of reproduction, potentially impacting algal populations and the ecosystems they support. Rising temperatures may alter the timing of reproduction, leading to mismatches with the availability of resources or the reproductive cycles of dependent organisms. Ocean acidification can affect the development and survival of algal spores, influencing recruitment and population dynamics. Excess nutrient input from human activities can lead to changes in algal communities, favouring species that can thrive in eutrophic conditions. Adaptation and resilience of marine algae in the face of environmental changes are subjects of ongoing research and conservation efforts [35], [40], [42]

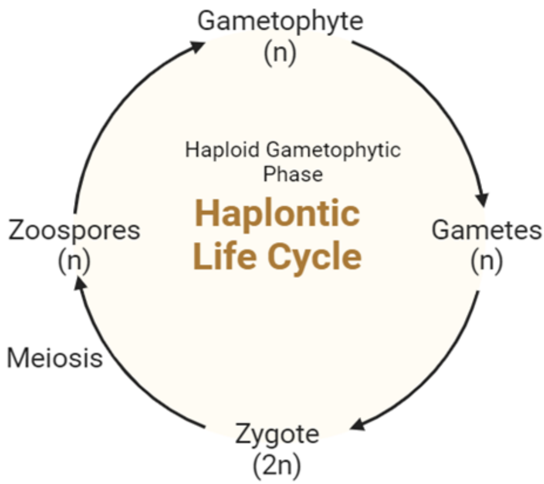

Fig 1-3: Haplontic life cycle of seaweeds

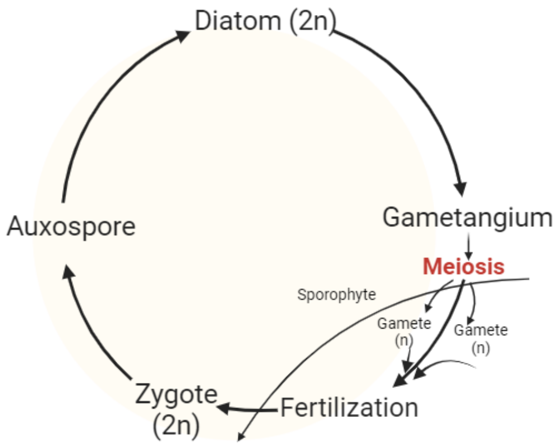

Fig 1-4: Diplontic life cycle of seaweeds

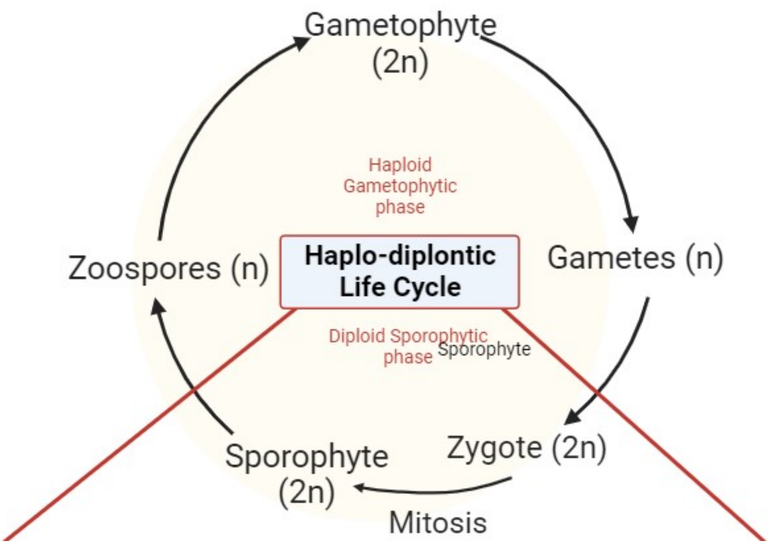

Fig 1-5: Haplo-diplontic life cycle of seaweeds

5. Utilization of Marine Seaweeds

5.1 Food Industry

Seaweeds have a long history of culinary use in many countries, particularly in Asia, where they are essential ingredients in dishes like sushi and nori rolls. They provide unique Flavors, textures, and umami tastes to food products. In the food industry, seaweeds are used in various forms, including dried, fresh, and processed products [43]. They are rich in essential nutrients, such as vitamins (e.g., vitamin C, B vitamins), minerals (e.g., iodine, calcium), and dietary fiber. Seaweeds are also a source of high-quality proteins, making it valuable for plant-based and vegetarian diets. The food industry has incorporated seaweeds in products ranging from snacks and condiments to soups and salads, tapping into their health benefits and nutritional value [44].

5.2 Pharmaceutical Industry

Seaweeds have gained recognition in the pharmaceutical industry due to their bioactive compounds and potential health benefits. These compounds include sulfated polysaccharides, polyphenols, and various secondary metabolites [45], [46]. Seaweeds exhibit antioxidant, anti-inflammatory, antiviral, and anticoagulant properties, making them valuable for medicinal and therapeutic purposes. Compounds like fucoidans, carrageenan, and laminarins have shown promise in the development of pharmaceutical products. Their applications range from wound healing and tissue regeneration to drug delivery systems. The pharmaceutical industry has tapped into the therapeutic potential of seaweeds for conditions like diabetes, cancer, and cardiovascular diseases.

5.3 Nutraceutical Industry

The nutraceutical industry focuses on products that bridge the gap between nutrition and pharmaceuticals, offering health benefits beyond basic nutrition. Seaweeds, with its rich nutrient content and bioactive compounds, have become valuable ingredients in nutraceutical products. Seaweeds are used in dietary supplements, functional foods, and beverages to promote various health outcomes, such as immune system support, weight management, and cardiovascular health. Nutraceutical products often contain seaweed extracts, which can be standardized for specific bioactive compounds. For example, brown seaweed extracts are used in weight management supplements due to their potential to inhibit fat absorption. Red seaweeds, with their antioxidant properties, are incorporated into products for immune support and skin health. [44]

5.4 Cosmetic Industry

The cosmetic industry harnesses the beneficial properties of seaweeds for skincare and beauty products. Seaweeds contain compounds that promote skin hydration, cell regeneration, and collagen production. They are rich in vitamins, minerals, and antioxidants that nourish and protect the skin. Seaweed extracts are used in a range of cosmetic products, including moisturizers, anti-aging creams, facial masks, and sunscreens. Seaweeds offer a natural alternative to synthetic ingredients, and their sustainable cultivation aligns with the growing consumer demand for eco-friendly and clean beauty products. Seaweed-derived ingredients, such as alginates and carrageenan, have gelling and thickening properties that enhance the texture and performance of cosmetics [47].

5.5 Sustainable Seaweed Farming

As the demand for seaweed-derived products continues to grow, sustainable seaweed farming practices have become crucial to meet industry needs while preserving marine ecosystems. Sustainable cultivation methods include integrated multitrophic aquaculture (IMTA), which combines seaweed farming with finfish and shellfish aquaculture, reducing environmental impact [48]. Open-sea cultivation and land-based seaweed farms are other approaches that emphasize responsible practices. Sustainable seaweed farming helps to protect natural seaweed populations, maintain water quality, and reduce the carbon footprint of production [49].

6. Significance for Pharmacological Research

6.1 Overview of the chemical compounds found in marine seaweeds

Marine macroalgae have been recognized as a prolific source of bioactive compounds with diverse chemical structures and biological activities. These compounds are often produced as a part of the algae's defense mechanisms, helping them survive in the challenging marine environment [50]. Over the years, researchers have identified and characterized a wide range of bioactive constituents from marine algae, revealing their potential for applications in medicine, food, cosmetics, and other industries. This exploration will take a deep dive into these common bioactive constituents and their significance (Figure 6).