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Review

Marine Algae in Wound Healing and Skin Regeneration: A Review of Bioactive Components

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Abstract

Marine algae, widely recognized as valuable marine resources, have gained increasing attention for their diverse bioactive compounds with therapeutic and cosmeceutical potential. Classified into green, brown, and red algae, they produce metabolites such as polysaccharides, polyunsaturated fatty acids, and phlorotannins, which exhibit strong antioxidant, antimicrobial, and anti-inflammatory activities. Key compounds like alginate, carrageenan, and phlorotannins plays vital role in wound healing, skin regeneration, and drug delivery systems due to their biocompatibility, biodegradability, and ability to enhance tissue repair. Alginates are extensively utilized in creams, gels, and biomedical patches for maintaining a moist wound environment and promoting healing. Carrageenans, derived from red algae, demonstrate antibacterial and photoprotective properties, making them suitable for cosmeceuticals and biomedical scaffolds. Phlorotannins from brown algae act as natural polyphenols with broad biological activities including UV protection and anti-aging effects, positioning them as promising ingredients in skincare formulations. Traditional uses of marine algae underscore their long-standing therapeutic significance, while modern research validates their application in advanced wound dressings, tissue regeneration, and controlled drug delivery. This review highlights marine algae as a sustainable and renewable source of innovative bioactive agents, presenting promising opportunities for pharmaceutical, cosmetic, and biomedical industries in the development of safe, natural, and effective therapeutic solutions.

Keywords: Alginate, Carrageenan, Phlorotannin's.

1.INTRODUCTION

Marine algae, sometimes referred to as seaweed or macroalgae, are eukaryotic photosynthetic organisms that are persistently alive along the coast. Based on their morphological colouration, macroalgae can be divided into three primary taxa: Phaeophycean, Chlorophyta, and Rhodophyta. Environmental elements that may affect the chemical makeup of marine algae include temperature, salt, sunshine, pH, physiological state, and CO_2 supply.

Different adaption techniques allow macroalgae to live in adverse environmental circumstances. In order to survive in a variety of environments, macroalgae must adapt by changing their physiology. As a result, they produce a variety of secondary metabolites. In a variety of environments, such as the desert and the arctic, macroalgae can even withstand very high or very low light levels.

Macroalgae create a range of naturally occurring bioactive substances and metabolites, including polysaccharides, polyunsaturated fatty acids, and phlorotannin's, in order to live in such diverse and harsh conditions. The bioactivities of the constituent parts of marine algae have been extensively examined since macroalgae are among the most frequently studied and utilised marine resources. Bioactive substances like polyphenols have anti-inflammatory, anti-cancer, antidiabetic, and antioxidant properties.[1]

Biomaterials developed from marine sources are biocompatible with humans. These days, the pharmaceutical business uses marine biomaterials, which are a renewable source of many substances. Seaweeds, sponges, crabs, and ascidians are among the marine species that provide various biomaterials. Protozoans, bacteria, fungus, chromista, animals, and plants are among the six kingdoms that include marine-derived organisms. These species are obtained in a unique way through exposure to various oceanic environmental conditions. Various elements obtained from marine sources are currently receiving increased attention and are used in a wide range of medications and dosage forms.

In order to identify novel molecular entities with advantageous properties derived from marine sources, marine pharmaceutics is crucial. Numerous highly significant biomaterials found in marine biodiversity eventually lead to pharmacological and medical discovery breakthroughs. Current research has been enhanced by the use of marine biomaterials in the pharmaceutical industry since they are inexpensive, plentiful, biocompatible, and biodegradable.

The kingdom of plants is home to endophytic fungus. A single plant can be colonised by several to hundreds of endophytes, and each connection is thought to be distinct yet classified as a hybrid of symbiotic and pathogenic. Although the relationship between endophytes and their plant hosts is not always clear, many endophytes improve host plant fitness by producing bioactive chemicals that increase plant growth and survival in the face of environmental stressors. Current drug development research focusses on these functional metabolites.[2]

2. MARINE SOURCE: AN UNEXPLORED POTENTIAL IN COSMETICS AND PHARMACEUTICALS

Marine pharmaceuticals have great potential as therapeutic agents for treating diseases like cancer, drug-resistant bacteria, viral infections, and immune-suppressive disorders. They are derived from a wide range of marine creatures, including bacteria, viruses, algae, fungi, and sponges. With many microorganisms actively creating these substances, the marine environment provides a rich supply of distinct and potentially life-saving bioactive secondary metabolites.

By investigating chemical structures obtained from marine sources, the pharmaceutical sector is well-positioned for a bright future in the creation of novel medications. Over 80% of the world's unique plant and animal species can be found in the oceans, which offer a huge and mainly unexplored pool of potential medicinal resources. Fish, sponges, tunicates, soft corals, sea hares, echinoderms, bryozoans, prawns, shells, sea slugs, and marine microorganisms are among the many marine creatures that act as [3]

3.TYPES

3.1Chlorophyceae (Green Algae)

Fig 1: Green Algae [4]

These algae can develop quickly and have the greatest capacity to take nutrients from seawater. Both freshwater and saltwater ecosystems are home to green algae. Green algae are reclassified using a DNA data bank. According to the most recent revision, green algae belong to the broader category known as Viridiplante, which also includes terrestrial plants. But all marine green algae belong to the same class, Ulyophyeae. With over 920 species spread across the globe, the Ulyophyceae is a highly diversified group.[5] Green algae with the pigments chlorophyll a and b are called chlorophyceae. (For example, Chara, Spirogyra, and Chlamydomonas).[6]

PHARMACOLOGICAL USES:
Anti-inflammatory, cytotoxic and immunosuppressive activities, antibacterial activity and antimutagenic activity.[7]

3.1.1. Euglena Gracilis

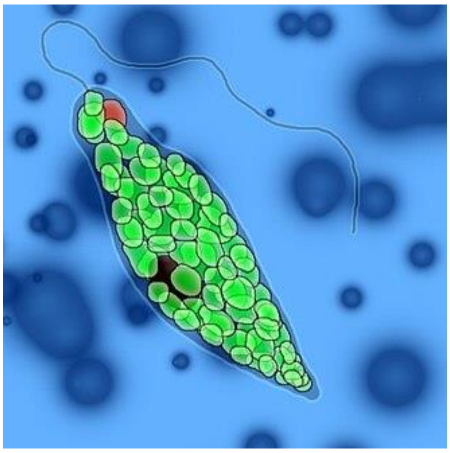

Fig 2: Euglena Gracilis [8]

Compounds of economic importance are found in the unicellular, photosynthetic protist Euglena gracilis, which is frequently compared to eukaryotic algae. When cultivated on organic carbon (i.e., in mixo- or heterotrophic conditions), E. gracilis accumulates paramylon, a form of β-1,3-glucan that is specific to euglenoids, notably Euglena species, for energy and carbon storage. Like other beta glucans, paramylon is thought to have anti-HIV and anti-tumor properties. [9]

FAMILY: Euglenaceae [10]

CHEMICAL CONSTITUENT: Lipids, paramylon, α-Tocopherol, Carotenoids, Euglenophycin. [11]

BIOLOGICAL SOURCE: Inhabit ponds with a lot of organic materials and fresh and brackish water. [12]

GEOGRAPHICAL SOURCE: Aquatic environments, including ponds, lakes, damp areas, and slowly moving rivers. [11]

USES: Anti-inflammatory, Antimicrobial, Antiviral, Antitumor [13]

3.2 Phaeophyceae (Brown algae)
Brown algae, or Phaeophyceae, are mostly found in marine environments. Dictyota, Laminaria, and Sargassum are examples of plants that contain pigments like xanthophyll, carotenoids, and chlorophyll A and C. [6]

Fig 3: Brown Algae [14]

Brown algae belong to the phylum Ochrophyta's Fucophyceae class. The total number of brown algae species is approximately 1780. Although they belong to the distinct kingdom of Chromsita, brown and green seaweeds coexist on rocky shorelines and share a similar macroscopical appearance. Although brown seaweeds are found all over the world, the polar region and cold-water nations are home to the greatest abundance of these algae, particularly the larger ones, such as Laminariales and Desmaresiales.[5]

PHARMACOLOGICAL USES: Cytotoxic and anti-tumour activity.[7]

3.2.1 Fucus Vesiculosus

Fig 4: Fucus Vesiculosus [15]

In the northern hemisphere, Fucus vesiculosus Linnaeus (Phaeophyceae, Fucales), a common brown alga that grows in cold and moderately cold waters along rocky coasts, is one of the most studied fucoidan producers. Because this alga is eurytopic, the phytochemical makeup of F. vesiculosus varies greatly based on its location and ontogeny. F. vesiculosus from the Barents Sea is unique in that it has a low amount of laminaran (no more than 2-3%) and a high amount of fucoidan (10-14%, and up to 18% in desalinated bays).[16]

FAMILY: Fucaceae [42]

CHEMICAL CONSTITUENT: Fucoidans, Polyphenols, Fucoxanthin, Essential minerals. [18]

BIOLOGICAL SOURCE: In marine waters that are often highly salinized, these algae are found in shallow-water macroalgae populations that are between 0.5 and 4 meters deep. [18]

GEOGRAPHICAL SOURCE: It typically inhabits the rocky, mild-littoral, and intertidal temperate coasts of Europe and North America. [42]

USES: Anti-oxidant, Anti-aging, Anti-microbial, Anticoagulant, Anti-inflammatory. [18]

3.3 Rhodophyceae (Red algae)

The red algae Porphyra, Gracilaria, and Gelidium are members of the Rhodophyceae family, which also contains the red pigment r-phycoerythrin. Blue-green algae (BGA) (Cyanobacteria) are the fourth type of algae and are sometimes mistaken for seaweed. This form of algae, also known as slime algae or smear algae, is frequently found in home aquariums where it quickly covers all surfaces.[6] Because to phycobilin pigments, algae might be pink, brilliant red, purple, or infrequently dark brown.[5]

Fig 5: Red Algae [17]

PHARMACOLOGICAL USES:
Antioxidant activities, Anti-inflammatory activities, Antifungal activities, Antiviral activities.[18]

3.3.1 PORPHYRIDIUM CRUENTUM

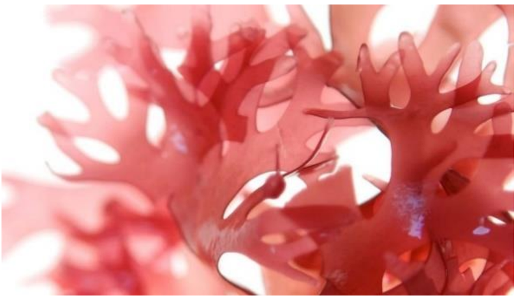

Fig 6: Porphyridium Cruentum [19]

Its ability to create B-phycoerythrin (B-PE), long chain polyunsaturated fatty acids (LC-PUFAs), and exopolysaccharides (EPS), which are superior feedstock for food, nutraceuticals, and medicines, has drawn a lot of attention recently. [20]

FAMILY: Porphyridiophyceae [21]

CHEMICAL CONSTITUENT:
It has a high polysaccharide content, occasionally reaching 57%. Additionally, phycoerythrin, a component of the proteins that give the cell its characteristic red colour, is present in a high percentage of the cell—up to 39% of the dry weight. Additionally, P. cruentum has a high proportion of unsaturated lipids, including arachidonic acid (AA), EPA, and DHA.[21]

BIOLOGICAL SOURCE: It can produce and secrete large amounts of PcSP into the culture medium, and it thrives in saline water. [22]

GEOGRAPHICAL SOURCE: The North-West Atlantic coasts and other naturally salty waters are home to the microalgae Porphyridium cruentum. [23]

USES: Antimicrobial, Anti-inflammatory, Antiviral, Skin protective activity. [24]

3.3 MARINE ALAGAE IN WOUND HEALING AND SKIN REGENERATION

The skin is a dynamic protective tissue that functions as a mechanical absorber and a strong barrier to keep out harmful substances and germs. Nonetheless, the skin is constantly harmed by a variety of physical and chemical processes. In order to recover its integrity and normal function, a damaged or wounded part of the skin sets off a complex and well-planned sequence of processes. A suitable microclimate with ideal moisture and oxygen levels as well as physical barriers to harmful bacteria is essential for quick and efficient tissue restoration through the healing process. Winter suggested using wound dressings in 1962 to create the ideal environment for wound regeneration. Numerous materials that potentially functionalize and speed up the wound healing process were investigated as a result of these findings. In previous decades, it has been suggested that gauzes, hydrogels, foams, hydrocolloids, and transparent films be used for the passive dressing of wounds that are healing. Tissue-engineered replacements have recently emerged as a viable option for skin tissue regeneration, especially for skin abnormalities brought on by trauma, burns, or persistent wounds that don't heal. Therefore, applications for wound healing and skin tissue regeneration have also evolved to incorporate biologically active natural and synthetic materials.[25]

3.4 ALGINATE

Fig 7: Alginates [26]

3.4.1 DEFINITION AND ITS COSMECETICAL USES

Alginates made from brown algae, like Turbin aria conoids and Fucus vesiculosus, have antioxidative qualities and help stop cutaneous diseases and skin aging. Antioxidants can also help preserve the organoleptic qualities of cosmetics by avoiding lipid oxidation, which stops flavour, texture, and Odour alterations. The structural elements of brown algal cell walls are polysaccharides called alginic acid and alginate salts. Alginates are utilized in a variety of creams, lotions, soaps, shampoos, foams, and gels as thickeners, stabilizers, and emulsifiers. Alginates are also frequently used in cosmetics as an ingredient in body wash and as a base for face masks and body lotions. Their purported ability to restore the structure and function of the skin by retaining water makes them an important ingredient in cosmetics. They are useful ingredients in the production of cosmetics because they have desirable gelling, viscosity-enhancing, and stabilizing properties. Alginates are derived from brown algae and utilized as thickening agents in a variety of goods, including ice cream and cosmetics.[27]

3.4.2 BIOMEDICAL PATCHES

Many biomedical applications, such as wound dressing, pharmaceutical, tissue regeneration, renewable energy, and 3D bioprinting applications, have been facilitated by alginate's exceptional biocompatibility and promising physicochemical characteristics.[28] By absorbing wound fluid to re-gel, dry alginate dressings can provide water to a parched wound, preserving a physiologically moist microenvironment and reducing the risk of bacterial infection at the wound site. Additionally, these actions can facilitate the production of granulation tissue, quick epithelialization, and healing.[29]

3.4.3 DRUG DELIVERY

Alginates have been thoroughly studied for drug delivery by transdermal, parenteral, pulmonary, and oral routes. Quercetin, isoniazid, rifampicin, ciprofloxacin, bovine insulin, and lentivectors have all been studied for controlled or sustained release distribution using alginate as a single polymer or the combination polymer. All formulations demonstrated improved drug entrapment efficiency, improved drug solubility and bioavailability, and decreased drug degradation. Alginate polymer-encapsulated chemotherapeutic drugs demonstrated improved target cell penetration. Alginate encapsulated with antigen demonstrated an improved immunological response.

Alginates have also been extensively studied for pulmonary drug delivery, leading to the development of paclitaxel-alginate microparticles that improved the site-specific efficacy of medications while lowering their toxicity. Inhalable particle delivery of doxorubicin and cisplatin for lung cancer treatment was investigated using alginate and PLGA polymers. BSA and BCG vaccines based on alginate have been used to test the effectiveness of smaller inhaled vaccines that offer greater protection and a higher immunogenic effect. It has been demonstrated that using alginate in transdermal delivery for wound dressing or wound healing can effectively provide a high porosity and prolonged release while also inhibiting pre-infection.[30]

3.5 CARRAGEENAN

Fig 8: Carrageenan [31]

3.5.1 DEFINITION

The general term "carrageenan" refers to a family of viscosifying and gel-forming polysaccharides that are extracted from specific red seaweed species. The class Rhodophyceae includes several seaweeds from which carrageenan is extracted. In the Atlantic Ocean close to Britain, Europe, and North America, this specific kind of seaweed is widespread. The EU additive E-number E407 or E407a is assigned to carrageenan when it is used in food items. In addition to having a slightly altered composition, E407a has a significant cellulose content. Despite having no nutritional value, carrageenan is employed in pharmaceutical applications as well as food preparation for its gelling, thickening, and emulsifying qualities. Carrageenan is a general term for a group of polysaccharides that have the ability to create gels and viscosities.[32]

3.5.2 USES IN COSMECEUTICALS

In both the culinary and non-food industries, carrageenan has found widespread use. Carrageenan is essential to the cosmetics industry because to its antibacterial, antioxidant, and photoprotective properties. Carrageenan has been used in the cosmetics industry because of its well-known thickening properties and tendency to produce films.[33]

3.5.3 BIOMEDICAL PATCHES

The prospective uses of carrageenan, which is derived from red algae, in the biological sciences have drawn more interest. Its exceptional biocompatibility, non-toxicity, and biodegradability in drug delivery systems, tissue regeneration, and wound healing make it advantageous for biomedical engineering applications. These properties enable carrageenan-based materials to integrate with biological settings and act as scaffolds or carriers that reduce unfavourable host reactions. Carrageenan's inherent bioactivity, which includes antiviral, antibacterial, and anticancer properties, makes it remarkable.[34]

3.5.4 DRUG DELIVERY

Its three key properties (a) its glycosidic bonds enable it to be broken down by hydrolase enzymes, resulting in biodegradability; (b) the sulphate groups in the CG are anionic and improve the behaviour of polyelectrolytes; and (c) the presence of hydroxyl groups provides the necessary interactions to produce chemical modifications help to explain the rise in the use of CG in drug delivery systems.

In these pharmaceutical formulations, CGs serve a variety of purposes, from the creation of coatings, matrices, stabilizers, binders, disintegrators, solubilizers, thickeners, and stabilizers to more intricate procedures like controlling drug release.

Drug delivery methods frequently use CG because it easily gels. These systems are typically created by heat-reversible gelation, ionic crosslinking, and altering the main chain of carrageenan. Their functional characteristics, stability, biodegradability, and biocompatibility are all determined by their chemical structure.[35]

3.6 PHLOROTANNINS

Fig 9: Phlorotannins [36]

3.6.1 DEFINITION

A form of naturally occurring active ingredient called phlorotannin's is taken from brown algae and is a significant plant polyphenol. In its structure, phloroglucinol is the fundamental unit. Phlorotannin's exhibit a broad spectrum of biological activities, including anti-inflammatory, anti-allergic, anti-bacterial, antiviral, anti-tumour, anti-hypertensive, hypoglycaemic, and whitening properties. The primary industries for phlorotannin's are food, medicine, and cosmetics.[37]

3.6.2 PHLOROTANNINS USED IN COSMECEUTICALS

According to reports, seaweeds are one of the abundant sources of novel bioactive chemicals with a range of biologically active qualities for possible industrial uses in functional foods, nutraceuticals, and cosmeceuticals. Phlorotannin's, one of the most significant naturally occurring secondary metabolic products with a variety of nutritional, functional, and bioactive qualities, are among the bioactive substances that have been separated from algae. On the other hand, phlorotannin's' characteristics make them suitable components for the cosmeceutical sector.[38]

3.6.3 BIOMEDICAL PATCHES

Numerous bioactivities, including antioxidant, antibacterial, anti-cancer, anti-inflammatory, anti-diabetic, and UV protection, are exhibited by phlorotannin's. Its antioxidant qualities are demonstrated by its claimed inhibition of the generation of reactive oxygen species and thiobarbituric acid reactive compounds. Polymeric phlorotannin's have recently been produced by cold plasma treatment to increase their antibacterial and radical scavenging capabilities.[39]

3.6.4 DRUG DELIVERY

Numerous biological activities are exhibited by phlorotannin's, such as hepatoprotective, neuroprotective, anti-inflammatory, anti-diabetic, anti-tumour and anti-hypertensive, antiviral, and antibacterial properties. The primary mode of delivery of polyphenols is by ingestion; hence, the bioavailability, absorption, and metabolism of phlorotannin's will influence their biological activity.[40]

3.7 TRADITIONAL USES OF MARINE ALGAE IN TREATMENT OF WOUND HEALING AND SKIN REGENERATION

Natural products have always been important to human existence. They were used as raw materials for medicine and eaten as food. Terrestrial plants, animals, and microbes were long thought to be the primary biological sources of natural goods. Their list was expanded to include a variety of marine organisms that differ significantly in taxonomy from terrestrial plants, animals, and microbes due to the ongoing discovery of the marine environment.

Because of the harsh circumstances found in the world's seas, a broad variety of natural compounds with distinctive structures are synthesised, contributing to the complexity and richness of marine ecosystems. Their varied biological characteristics have made them a valuable and distinctive technological raw material for making commercial goods that are in high demand in the biomedicine industry, both as therapeutic components of wound dressings and as matrices.[41]

CONCLUSION

The ocean's premium has yielded a collection of bioactive compounds from marine algae. It emerged from the hope in pursuit of optimal wound healing and skin regeneration. This review highlights the remarkable antimicrobial, anti-inflammatory, and antioxidative properties of marine algae-derived compounds. Their natural origin and therapeutic potential make them promising ingredients for advanced skincare and biomedical applications.

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