RESEARCH PAPER

MARINE ALGAE IN THE BLUE ECONOMY: UNLOCKING BIOACTIVE POTENTIAL FOR PHARMACEUTICAL AND COSMECEUTICAL INNOVATIONS

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ABSTRACT
Marine algae are receiving considerable attention as a rich source of bioactive compounds, and the blue economy has emerged as a sustainable paradigm for the use of marine resources. It is known that both macroalgae (seaweeds) and microalgae produce structurally diverse metabolites with a variety of biological activities, such as polyphenols, sulfated polysaccharides, carotenoids, peptides, and sterols. This review highlights the potential of marine algae as a sustainable source for drug discovery and cosmeceutical innovation. Compounds derived from algae have shown promising pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, anticancer, and antiviral activities. These bioactive compounds are crucial in the cosmetics industry for brightening the skin, protecting it from the sun, and healing wounds, mainly by modulating important molecular pathways like NF-κB, MAPK, Nrf2, and melanogenesis-related signalling. Furthermore, marine algae support sustainability objectives because of their rapid growth, capacity to sequester carbon, and low dependence on arable land. Despite these advantages, challenges such as variability in bioactive composition, extraction scalability, and limited clinical validation remain. Overall, marine algae represent a promising and sustainable frontier for future drug and cosmeceutical development within the blue economy framework.

Keywords: Marine Algae, blue economy, bioactive compounds, cosmeceuticals.

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INTRODUCTION

The global shift towards sustainable development has intensified the exploration of oceanic resources under the framework of the Blue Economy, which emphasizes the responsible utilization of marine biodiversity for economic growth, environmental preservation, and social well-being.[1] Within this paradigm, marine algae have emerged as one of the most promising and underexploited biological resources due to their immense diversity, adaptability, and biosynthetic capabilities.[2] Found across a wide spectrum of marine habitats—from shallow coastal waters to deep-sea ecosystems—marine algae include macroalgae (brown, red, green, golden and blue-green seaweeds) and microalgae (unicellular photosynthetic organisms), each contributing uniquely to marine ecosystems and biotechnological applications [3].

Marine algae are prolific producers of structurally diverse primary and secondary metabolites, shaped by evolutionary pressures such as salinity fluctuations, UV radiation exposure, and competition in marine environments.[4] These stress-adaptive mechanisms lead to the synthesis of unique compounds, including sulfated polysaccharides (fucoidan, carrageenan, and ulvan), polyphenols (phlorotannins), carotenoids (fucoxanthin, astaxanthin), alkaloids, peptides, and omega-3 fatty acids.[5] Such compounds have attracted considerable interest in the field of drug discovery due to their multifaceted pharmacological properties, including antioxidant, anti-inflammatory, antimicrobial, antiviral, anticancer, anti-diabetic, and neuroprotective activities. Importantly, many of these molecules exhibit novel mechanisms of action, offering opportunities to address unmet medical needs and combat drug resistance [6].

In recent years, technological advancements in marine biotechnology, genomics, metabolomics, and bioinformatics have revolutionized the screening and identification of bioactive compounds from marine algae.[7] High-throughput

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screening platforms and in silico approaches, such as molecular docking and systems biology, have accelerated the discovery pipeline, enabling the identification of lead compounds with high specificity and efficacy [8].Furthermore, innovative drug delivery systems—including nanoparticles, liposomes, and micro-needle-based formulations—are being developed to enhance the bioavailability and targeted delivery of algal-derived therapeutics, aligning with modern pharmaceutical strategies [9].

Parallel to pharmaceutical applications, marine algae have gained substantial prominence in the rapidly expanding cosmeceutical sector, which lies at the interface of cosmetics and therapeutics.[10] The incorporation of algal bioactive into skincare and personal care products is driven by their natural origin, biocompatibility, and multifunctional properties. Algal polysaccharides contribute to skin hydration and barrier function, while antioxidants such as carotenoids and polyphenols protect against oxidative stress and photo-aging[11]Compounds like fucoxanthin and phlorotannins have demonstrated the ability to modulate melanogenesis, making them valuable in skin-whitening and anti-hyperpigmentation formulations[12]. Additionally, marine algae-derived ingredients have shown potential in wound healing, anti-acne, anti-inflammatory, and anti-pollution skincare applications, addressing contemporary dermatological concerns [11].

From an environmental and economic standpoint, marine algae represent a sustainable and scalable resource. Unlike terrestrial crops, algae cultivation does not require arable land, freshwater, or synthetic fertilizers, thereby reducing ecological footprints[13]. Moreover, large-scale seaweed farming contributes to carbon sequestration, nutrient removal from eutrophic waters, and marine ecosystem restoration.[13] These attributes position marine algae as a cornerstone of sustainable biorefineries, where biomass can be fractionated into multiple high-value products, ensuring maximum resource efficiency and minimal waste generation. [14]This integrated approach aligns with circular economy principles and enhances the commercial viability of algal industries. Furthermore, the study will explore the efficacy of these algal extracts in mitigating hyperpigmentation, given the well-documented anti-tyrosinase activity of certain seaweed compounds.[15]

Despite these advantages, several challenges hinder the full-scale exploitation of marine algae in drug discovery and cosmeceutical innovation.[16] These include variability in chemical composition due to environmental factors, difficulties in large-scale cultivation and harvesting, challenges in standardizing and quality control of bioactive extracts, and stringent regulatory frameworks governing marine-derived products.[17]Additionally, translating promising in vitro and in vivo findings into clinically approved products remains a significant bottleneck, necessitating interdisciplinary collaboration and robust validation strategies.[18] This rigorous assessment ensures that selected algal extracts meet stringent efficacy and safety criteria, thereby providing a robust foundation for their commercial application in advanced dermatological formulations.[19] The investigation will also consider the biocompatibility of these extracts to ensure they are suitable for cosmeceutical applications, focusing on low or non-toxic effects on human cells[20]. In this context, the present review aims to comprehensively explore the role of marine algae within the Blue Economy, focusing on their biochemical diversity, therapeutic potential, and applications in cosmeceutical development.[21]

BACKGROUND

Marine algae have been utilized for centuries across coastal civilizations as sources of food, traditional medicine, and agricultural inputs, particularly in regions such as East Asia, where seaweeds form an integral part of daily life [22]. Historically, these organisms were valued for their nutritional richness, including essential vitamins, minerals, and polysaccharides, as well as their therapeutic benefits in treating ailments such as goiter, inflammation, and skin disorders.[23] However, it is only in recent decades that marine algae have gained global scientific and industrial attention as reservoirs of novel bioactive compounds, largely driven by advances in marine science and the growing demand for sustainable bioresources.[5]

The emergence of the Blue Economy has further accelerated interest in marine algae by promoting the sustainable exploitation of oceanic resources for economic growth while maintaining ecological balance.[24] Within this framework, algae are increasingly recognized as a renewable and scalable biomass with diverse applications spanning pharmaceuticals, nutraceuticals, biofuels, and cosmeceuticals.[25] Global seaweed production has expanded significantly over the past few decades, with aquaculture contributing the majority of supply, particularly from countries such as China, Indonesia, and South Korea. This rapid growth reflects both the economic viability and environmental benefits of algal cultivation.[26]

From a pharmaceutical perspective, marine algae represent a largely untapped source of structurally unique natural products. Unlike terrestrial plants, marine organisms are exposed to distinct environmental stressors such as high salinity, variable light intensity, and intense ecological competition, which drive the production of chemically diverse and biologically active metabolites.[5] These compounds have demonstrated promising activities in various therapeutic areas, including cancer, infectious diseases, metabolic disorders, and neurodegenerative conditions.[27] The integration of marine-derived compounds into the drug discovery pipeline has led to the identification of several lead molecules, some of which are currently undergoing preclinical and clinical evaluation.[28]

In parallel, the cosmeceutical industry has witnessed a paradigm shift toward the use of natural and marine-derived ingredients, driven by consumer preference for safe, sustainable, and multifunctional products.[11] Marine algae-derived compounds, such as polysaccharides, antioxidants, and pigments, have been widely incorporated into skincare formulations due to their proven efficacy in hydration, anti-aging, photoprotection, and skin repair.[29] Their ability to modulate key biological processes, including collagen synthesis, inflammation, and melanogenesis, makes them highly valuable in addressing a broad spectrum of dermatological concerns.[30]

Technological advancements have played a crucial role in unlocking the potential of marine algae. Modern tools such as high-throughput screening, metabolomics, and bioinformatics have enabled the rapid identification and characterization of bioactive molecules.[31] Additionally, innovations in extraction techniques, such as supercritical fluid extraction and green chemistry approaches, have improved the efficiency and sustainability of compound isolation.[32] Despite these advancements, several challenges remain, including variability in biomass composition, scalability issues, and regulatory constraints associated with marine-derived products.[11] Addressing these challenges is essential to fully harness the potential of marine algae as a cornerstone of sustainable innovation in drug discovery and cosmeceuticals.[11]

RATIONALE FOR EXPLORATION

The growing demand from consumers for natural, safe, and effective skincare products underscores the importance of thoroughly studying the bioactive properties of seaweed extracts for use in dermatology.[33] This study is especially important because consumers are increasingly concerned about the environmental effects of synthetic ingredients, and the cosmetic industry is moving toward more sustainable sourcing.[33] Seaweeds are a highly promising and environmentally friendly alternative to traditional synthetic ingredients because they are abundant, renewable, and contain a wide range of bioactive compounds[34]. To fully realize their potential for new cosmetic and therapeutic uses, it is necessary to thoroughly investigate their phytochemical composition and biological activities.[35] This study aims to synthesize existing knowledge on the antihyperpigmentation, antimicrobial, and antioxidant properties of algal extracts, rigorously assessing their effectiveness through in silico, in vitro, and in vivo approaches.[36] This in-depth study will elucidate the mechanisms of action of these marine-derived ingredients, identify promising compounds, and address challenges and necessary steps for their effective integration into cosmeceutical formulations.[37]

DIVERSITY OF SEAWEEDS

These phlorotannins, through their multifaceted mechanisms, including direct radical scavenging and enzyme inhibition, exemplify the high-value compounds obtainable from marine sources for dermatological applications [38]. This section categorizes marine macroalgae into distinct phylogenetic groups: brown algae, green algae, and red algae, each characterized by unique pigments, structural polysaccharides, and secondary metabolites that contribute to their diverse bioactive properties [39]. These distinct biochemical profiles dictate their specific applications in cosmeceuticals, particularly concerning their anti-hyperpigmentation, antimicrobial, and antioxidant capacities [29]. Understanding these distinctions is crucial for targeted bioprospecting and the rational design of novel cosmeceutical formulations that harness the specific benefits offered by each algal type [29]. Furthermore, the ecological niches occupied by various seaweed species influence their secondary metabolite production, necessitating an examination of this environmental variability in relation to their pharmacological potential [40].

Brown Algae (*Ochrophyta, Phaeophyceae)*

Brown algae are characterized by their dominant fucoxanthin pigment, which imparts a brownish-green hue[41], and their cell walls contain alginates and fucoidans. They also contain laminarin as a storage polysaccharide[42]. These complex carbohydrates contribute to their structural integrity and exhibit diverse biological activities, including antioxidant and anticoagulant properties[5]. They are also prolific producers of phlorotannins, a unique class of polyphenolic compounds exclusive to brown seaweeds, which exhibit potent antioxidant, anti-melanogenic, and photoprotective effects [43]. This rich biochemical profile underscores their significant potential in dermo-cosmetic applications, particularly in the development of anti-aging and skin-protective formulations [44]. Extracts from species such as *Undaria pinnatifida* and *Undaria japonica* are widely recognized for their efficacy in promoting skin hydration and reducing hyperpigmentation [45]. Their widespread distribution and renewable nature further enhance their appeal as sustainable sources for cosmetic ingredients [46]. The ecological viability and cost-effectiveness of cultivating or harvesting these marine resources are also crucial considerations for their sustainable integration into industrial applications [47]. The distinct biochemical characteristics of brown algae enable their extensive utilization across various sectors, including nutricosmetics, pharmaceuticals, and functional foods, underscoring their economic and scientific significance [48]. *Undaria pinnatifida*(Figure-1a), a prominent species of brown algae, is particularly recognized for its fucoidan content, a sulfated polysaccharide with noted anti-inflammatory and antioxidant properties [49]. Kelp(Figure-1d) also is a significant source of alginates and phlorotannins, further extending their utility in biomedical and cosmetic applications [50].

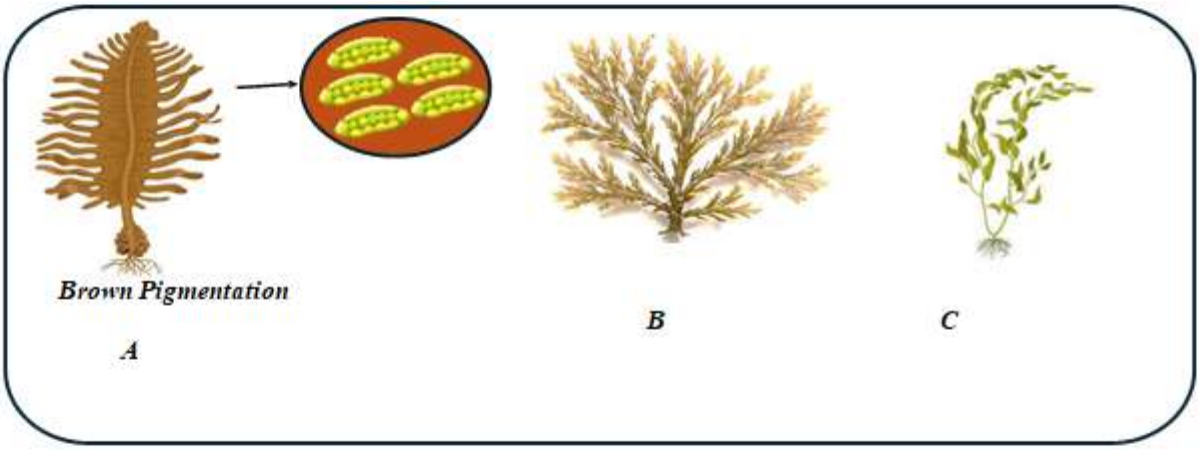

Fig.1. ***Brown Algae (Ochrophyta, Phaeophyceae). A. Undaria pinnatifida, B. Sargassum, C. Giant Kelp***

Green Algae (Chlorophyta)

Green algae, or Chlorophyta, are distinguished by their primary photosynthetic pigments, chlorophyll a and b, which give them their characteristic vibrant green color. Their cell walls are predominantly composed of cellulose and various sulfated polysaccharides.[51] These polysaccharides, such as ulvans, possess significant biological activities including immunomodulatory, antiviral, and antioxidant properties, making green algae a valuable source for bioactive compounds in cosmeceuticals and pharmaceuticals. [52] Their phytochemical profiles often include carotenoids, such as lutein and zeaxanthin, along with a variety of phenolic compounds and sterols, contributing to their broad spectrum of health-promoting benefits. [53]

For example, species like Ulva lactuca(Figure-2a) and Chlamydomonas reinhardtii(Figure-2b) are explored for their anti-inflammatory and skin-rejuvenating effects [54]. Their widespread distribution in aquatic and even terrestrial environments across diverse regions further highlights their accessibility and potential for sustainable harvesting for biotechnological applications [54]. The diverse biochemical composition of green algae, encompassing a range of polysaccharides, pigments, and secondary metabolites, offers a compelling natural alternative to synthetic ingredients in the development of advanced skincare products [55].

For instance, Ulva lactuca has been extensively studied for its rich polysaccharide content, phenolic compounds, and fatty acids, which contribute to its antioxidant, anti-inflammatory, and neuroprotective properties, making it a promising ingredient for skin health enhancement [56]. Similarly, Chlamydomonas reinhardtii is notable for its capacity to produce a diverse array of bioactive compounds, including high-value carotenoids and peptides, which exhibit promising skin-protective and regenerative properties [57].

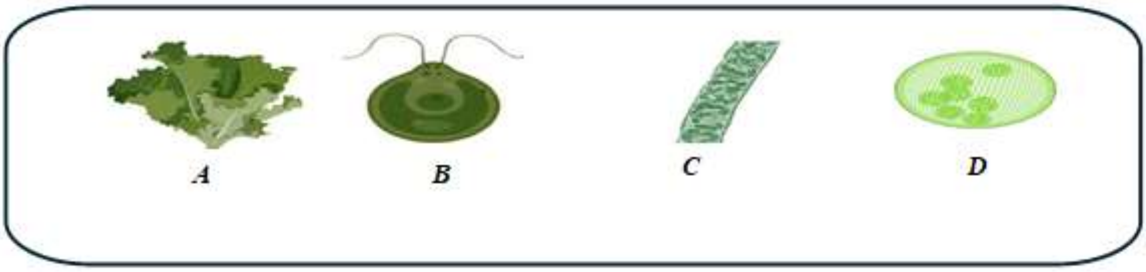

Fig.2.*Green Algae(*Chlorophyta*).A.Ulvalactuca, B.Chlamydomonasreinhardtii, C.Spirogyra, D.Volvox*

Red Algae (Rhodophyta)

Red algae derive their characteristic red coloration from phycobiliproteins like phycoerythrin and phycocyanin, which mask chlorophyll a and other accessory pigments [58]. These organisms also contain diverse sulfated galactans, such as carrageenans and agars, which provide structural support and exhibit a range of pharmacological effects including anti-inflammatory, anticoagulant, and immunomodulatory activities [59]. Furthermore, red algae are a rich source of mycosporine-like amino acids, which offer potent UV-absorbing and antioxidant properties, making them highly relevant for photoprotective cosmetic applications [60]. Their distinct pigment compositions, including chlorophylls, phycobiliproteins, and xanthophyll, also contribute to their diverse biological activities and chemotaxonomic classification [61]. The substantial carbohydrate content, ranging from 40-70%, primarily in the form of glucans, cellulose, and galactans, further highlights their potential for biotechnological exploitation beyond pigments [34].

Certain species, such as Porphyra spp. and Gracilaria spp., are extensively cultivated for their high-value phycocolloids and nutraceutical compounds, further emphasizing their commercial significance [62]. Their cultivation also provides a sustainable source for food, feed, and various industrial applications, including the production of biofuels and pharmaceuticals [63].

Membranoptera platyphylla(Figure-3a), a red algal species, is particularly noted for its significant concentrations of phycobiliproteins, sulfated polysaccharides, and mycosporine-like amino acids, which collectively contribute to its robust antioxidant and UV-protective capabilities [64]. These red algae also produce valuable compounds such as β-carotene and zeaxanthin carotenoid pigments, alongside heat-stable phycocyanin, which possess antioxidant, anti-inflammatory, and anti-cancer attributes [65].

Chondrus crispus (Figure-3c), rich in carrageenans, which are sulfated polysaccharides with recognized applications in food science and biomedicine due to their gelling and immunomodulatory properties [66]. Specifically, carrageenans from Chondrus crispus are high-molecular-weight sulfated polysaccharides composed of d-galactose and 3,6-anhydro-d-galactose monomers, alternately linked by α-1,3 and β-1,4 glycosidic linkages, which confer a broad spectrum of beneficial activities such as anti-hyperlipidaemia, immunomodulation, anticoagulant, antioxidant, and antiviral effects [67].

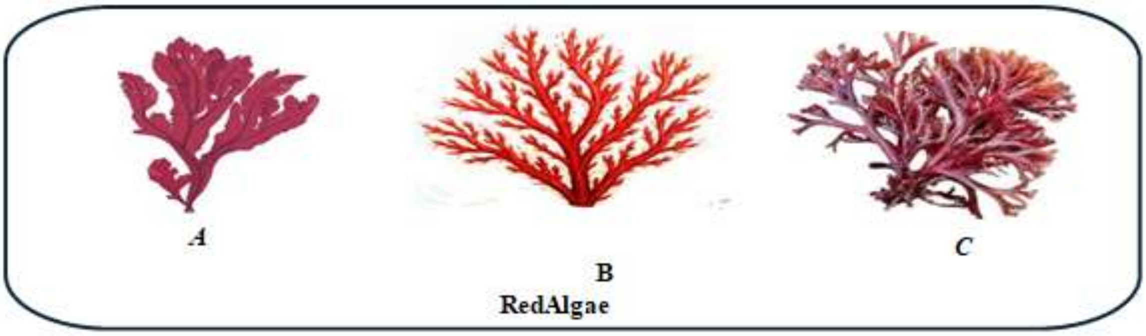

Fig.3.Red *Algae*(Rhodophyta). *A. Membranopteraplatyphylla, B.*BranchedRedAlgae*, C.ChripusChondrus*

Blue-Green Algae (Cyanobacteria)

Cyanobacteria, commonly referred to as blue-green algae, are prokaryotic photosynthetic organisms that possess phycobiliproteins, similar to red algae, which contribute to their diverse coloration and are associated with a variety of bioactive compounds. These organisms are characterized by the presence of chlorophyll a and phycobilins such as phycocyanin and phycoerythrin, which enable them to thrive under diverse light conditions [68]. Cyanobacteria are a significant source of biologically active natural products, including vitamins, proteins, and fine chemicals, presenting substantial opportunities for discovering novel compounds with antibacterial, antiviral, and antifungal properties [69]. Moreover, their capacity to produce a wide array of secondary metabolites, such as toxins, pigments, and enzymes, underscores their ecological significance and potential for biotechnological exploitation [70]. For example, Spirulina platensis and Arthrospira maxima are renowned for their high protein content and antioxidant pigments like phycocyanin, making them valuable in nutritional supplements and pharmaceuticals [71].Spirulina platensis(Figure-4a) exhibits a wide array of beneficial properties, including anti-hyperpigmentation, antimicrobial, and antioxidant activities, primarily attributed to its unique biochemical composition [72]. Arthrospira maxima(Figure-4b) is rich in phycobiliproteins, particularly C-phycocyanin, which confers potent antioxidant and anti-inflammatory effects [73]. These species also contain various polysaccharides, carotenoids, and phenolic compounds, which further contribute to their diverse pharmacological profiles, including neuroprotective and immunomodulatory effects [74].

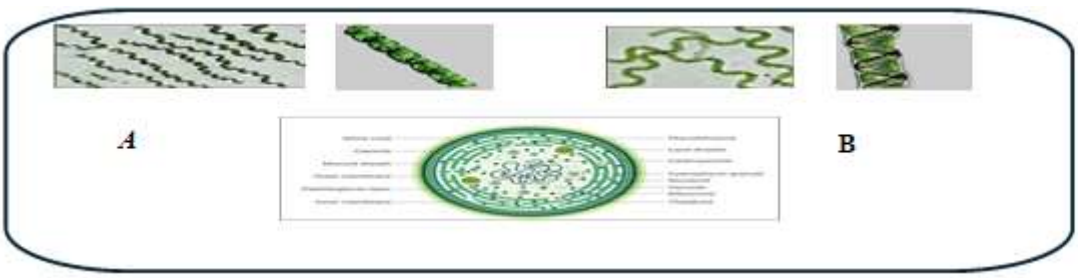

Fig. 4.Blue-greenAlgae (Cyanobacteria).*A.Spirulinaplatensis, B. Arthrospira maxima*

GoldenAlgae(Chrysophytes)

Golden algae, primarily diatoms and chrysophytes, constitute a diverse group characterized by their distinctive golden-brown chloroplasts containing fucoxanthin and other carotenoids, which contribute to their photosynthetic efficiency and serve as a source of valuable bioactive compounds. These pigments, along with a high content of polyunsaturated fatty acids, distinguish golden algae as a promising resource for pharmaceutical, nutraceutical, and cosmeceutical applications [75] .

The unique biochemical profiles of golden algae, particularly their fucoxanthin content, are increasingly recognized for their potent anti-inflammatory, anticancer, and anti-obesity effects, warranting further investigation into their therapeutic potential [76]. This highlights the necessity of in-depth studies into their cultivation, extraction, and purification processes to harness their therapeutic benefits and fully ensure sustainable production. Their rich lipid content, including eicosapentaenoic acid and docosahexaenoic acid, further enhances their biomedical relevance, particularly in cardiovascular and neurological health [77].

Synura spp. and *Mallomonas* spp. are commonly cited as golden algae, particularly for their unique silica scales and flagella structures, which are critical for taxonomic identification and ecological functions in freshwater environments. Similarly, *Synura* species are primarily known for their ecological roles, further research is required to fully elucidate any direct pharmacological effects or potential toxicological considerations for human consumption [78]. While *Mallomonas* species are primarily recognized for their ecological roles as producers in freshwater ecosystems and as indicators of water quality due to their silicified scales, their direct pharmacological or toxicological properties in humans remain largely unexplored [79].

Phaeodactylum tricornutum **(Figure-5)** notable example among golden algae, highly valued for its abundant intracellular fucoxanthin and eicosapentaenoic acid, both of which possess significant physiological activities, including antioxidant, anti-inflammatory, and antitumor effects [80].

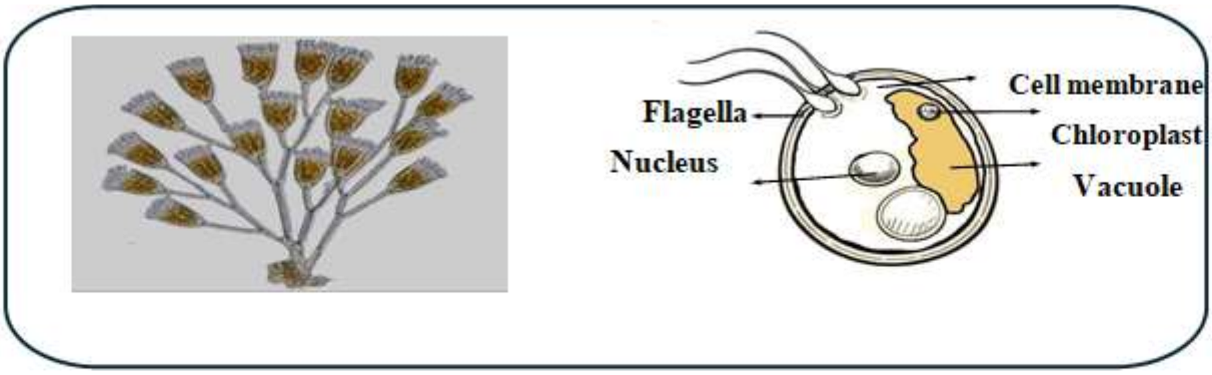

Fig.5.*Golden Algae (*Chrysophytes*). A. Tisochrysislutea*

CHEMICAL COMPOSITION OF SEAWEED

The diverse chemical composition of seaweeds, encompassing a wide array of primary and secondary metabolites, underpins their extensive biological activities and potential as a rich source of novel bioactive compounds for various industrial applications [81]. These compounds include high-quality proteins, dietary fibres, essential macro- and micronutrients, vitamins, minerals, and fatty acids, all of which are valuable for cosmetic and pharmaceutical industries [82]. Specifically, the presence of certain polysaccharides, polyphenols, and peptides positions seaweeds as exceptional natural reservoirs for anti-hyperpigmentation, antimicrobial, and antioxidant agents, which are highly sought after in advanced dermo-cosmetic formulations [29]. Their complex chemical makeup, which often includes unique organic compounds not synthesized by terrestrial plants, offers a vast and largely unexplored biochemical library for drug discovery and cosmeceutical innovation [83].

Numerous studies have highlighted the versatile nature of seaweed-derived metabolites, showcasing their utility across pharmaceutical, nutraceutical, and cosmetic sectors [83]. This extensive biochemical repertoire makes seaweeds an attractive and sustainable resource for developing innovative products across a multitude of industries [84]. Further investigation into these intricate molecular structures and their synergistic effects is crucial for unlocking their full therapeutic and industrial potential [85].

Polysaccharides

Seaweed polysaccharides, such as alginates, carrageenans, and fucoidans (Figure-11), are complex carbohydrates that contribute significantly to the structural integrity of the algal cell wall and possess a broad spectrum of bioactivities, including anticoagulant, antiviral, and anti-inflammatory properties [86]. Other high-value compounds, such as polyunsaturated fatty acids, proteins, and polyphenols, are sustainably sourced from wild and cultivated kelps, underscoring their potential for blue biotechnology [87]. These complex biopolymers, extracted from various seaweed species, are also recognized for their significant roles in immunomodulation and tumor inhibition, offering promising avenues for pharmaceutical development [10]. The majority of seaweed biomass is composed of these polysaccharides, which has spurred significant interest in their commercial applications, particularly in the production of agar (Figure 6), carrageenan (Figure 7), and alginate [88]. These hydrocolloids are widely utilized in the food, pharmaceutical, and cosmetic industries as gelling agents, stabilisers, and emulsifiers, owing to their unique physicochemical properties [83]. Moreover, sulfated polysaccharides from brown seaweeds, such as laminaran (Figure 8), exhibit anti-diabetic, anti-obesity, and UV-protective effects, further expanding their therapeutic utility [89]. Beyond their structural and gelling properties, these diverse polysaccharides are also being explored for their potential in drug delivery systems and tissue engineering, owing to their biocompatibility and biodegradability [88]. Their diverse structures and functional groups allow for chemical modifications, enabling the tailored design of novel biomaterials with enhanced therapeutic efficacy [90]. Specifically, agar, a polysaccharide extracted predominantly from red algae such as Pterocladiella, Gelidium amansii, and Gracilaria, is valued for its antioxidant and thickening properties, and is used as a gelling agent and in various biomedical fields [34]. Carrageenan (Figure 7), another sulfated polysaccharide abundantly present in red seaweeds, constitutes a major component of algal cell walls and accounts for up to 40–50% of the dry weight, alongside agar [64].

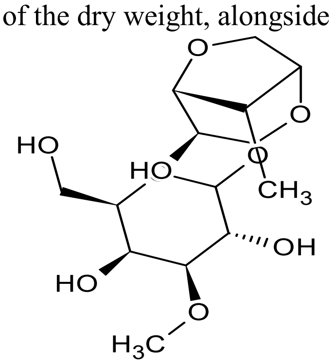

Fig.6. Idealised structure of agar

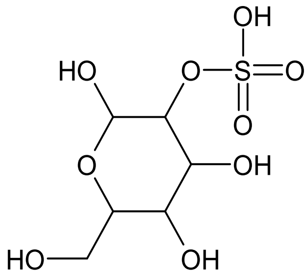

Fig.7. Idealised structure of kappa-carrageenan

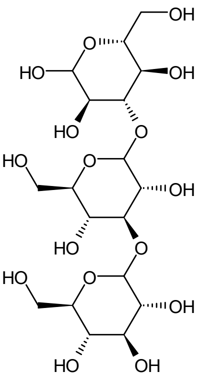

Fig.8. Idealised structure of the chemical units of laminaran

Polyphenols

These galactans, primarily kappa, iota, and lambda-carrageenans (Figure 7), are particularly notable for their gelling, thickening, and emulsifying properties, making them indispensable in various industrial applications [41]. Alginate, another prominent polysaccharide found in brown seaweeds such as Ecklonia radiata, is utilized in food products, pharmaceuticals, textile printing, and cosmetics for its gelling properties. Beyond their gelling capabilities, alginates have also demonstrated significant potential in wound healing applications due to their biocompatibility and ability to form a protective hydrogel[91]. Ecklonia cava is a rich source of phlorotannins like Eckol (Figure 9), Dieckol (Figure 10) and Phlorofucofuroeckol A, a class of polyphenolic compounds exclusively found in brown algae, which exhibit potent antioxidant, anti-inflammatory, and anti-carcinogenic activities [92].

Other bioactive compounds, such as oligosaccharides, polyunsaturated fatty acids, sterols, proteins, polyphenols, carotenoids, vitamins, and minerals, also contribute to the diverse pharmacological properties of seaweeds [93]. Among these, polyphenols, particularly phlorotannins found in brown algae, are recognized for their potent antioxidant and anti-inflammatory activities, which stem from their unique structural complexity and high affinity for free radicals [94]. Phlorotannins, a type of tannin exclusive to brown algae, are synthesized through the polymerization of phloroglucinol units and exhibit diverse structures ranging from simple monomers to complex polymers with molecular weights exceeding 100 kDa [95]. Their potent radical-scavenging capabilities and chelating properties enable them to effectively neutralize reactive oxygen species, thereby mitigating oxidative stress implicated in various chronic diseases [96]. Moreover, the structural diversity of phlorotannins contributes to their varied biological activities, including antimicrobial and anticancer effects, making them valuable candidates for drug development [97].

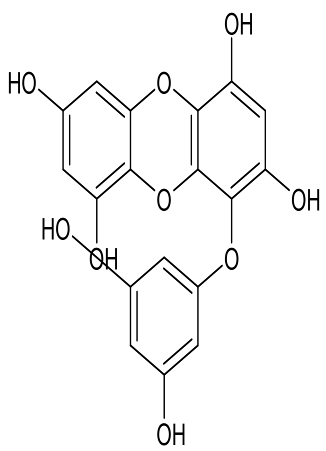

Fig.9. Eckol

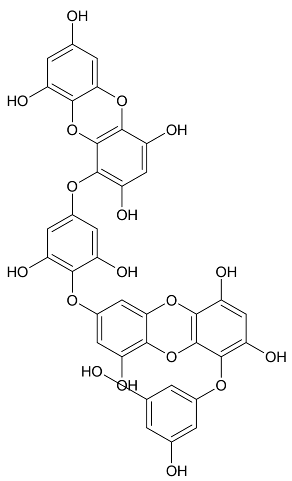

Fig. 10. Idealised structure of Dieckol

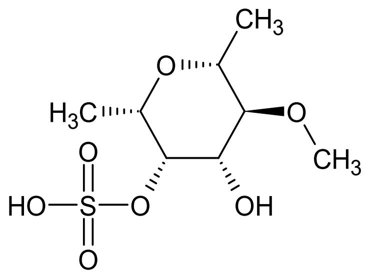

Fig.11. Idealised structure of fucoidan

Peptides

Peptides derived from seaweeds, often generated through enzymatic hydrolysis of algal proteins, exhibit a wide array of therapeutic properties, including antioxidant, antihypertensive, and antimicrobial activities [98]. These bioactive peptides often possess specific amino acid sequences that confer their functional attributes, influencing cellular signaling pathways and enzyme activities [99]. For instance, peptides rich in hydrophobic amino acids frequently demonstrate enhanced antioxidant capacity due to their ability to interact with lipid environments and sequester free radicals [100]. Furthermore, the enzymatic hydrolysis conditions and the specific algal species used can significantly influence the profile and bioactivity of the resulting peptides [101]. For instance, certain seaweed peptides have shown the ability to inhibit enzymes involved in melanin synthesis, thereby offering potential anti-hyperpigmentation effects [102]. The bioavailability and efficacy of these peptides are influenced by their amino acid sequences and structural conformations, which dictate their stability and interaction with specific biological targets [103]. Additionally, marine algal peptides can act as signaling molecules, modulating cellular pathways involved in inflammation and oxidative stress, thereby contributing to their therapeutic effects[104] . This extensive array of phytochemicals underscores the significant potential of seaweeds as a source for novel drug discovery, particularly in addressing conditions linked to oxidative stress and inflammation [105].

Pigments

Seaweed pigments, such as carotenoids(Figure-13) and chlorophylls (Figure-12), are potent antioxidants and exhibit a range of biological activities, including anti-inflammatory, anticancer, and photoprotective effects [106]. These compounds are essential for photosynthesis and play a crucial role in protecting seaweeds from harmful UV radiation and oxidative stress, thereby offering similar protective benefits when extracted and applied in various bio-applications [34]. For instance, fucoxanthin (Figure-12), a prominent carotenoid in brown seaweeds, has garnered significant attention for its anti-obesity and anti-diabetic properties, alongside its considerable antioxidant capacity [35]. Similarly, phycobiliproteins(Figure-12), found in red algae, are water-soluble pigments known for their strong antioxidant and anti-inflammatory activities, further contributing to the therapeutic potential of seaweed extracts [39]. Additionally, the structural diversity of these pigments, including their chromophore arrangements and protein interactions, contributes to their varied light-harvesting efficiencies and distinct pharmacological profiles [107]. These diverse pigments contribute significantly to the overall antioxidant potential of seaweeds, providing robust defence against oxidative stress through multiple mechanisms [34]. Specifically, phycobilins, chlorophylls (Figure-12), and carotenoids(Figure-13) collectively scavenge reactive oxygen species and inhibit lipid peroxidation, offering substantial protective effects against oxidative damage [108]. Beyond their primary antioxidant functions, these natural pigments also exhibit anti-inflammatory, immune-modulatory, and neuroprotective properties, suggesting a broad spectrum of health benefits [109].

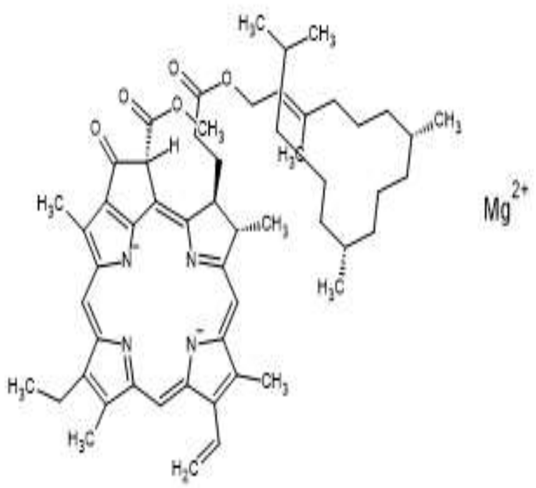

Fig.12. Idealised structure of Chlorophyll a

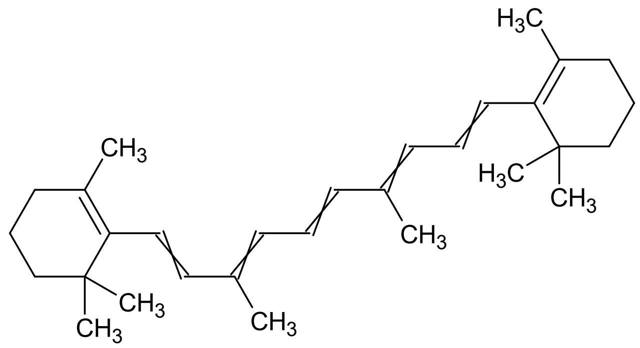

Fig.13. Idealised structure of β-carotene

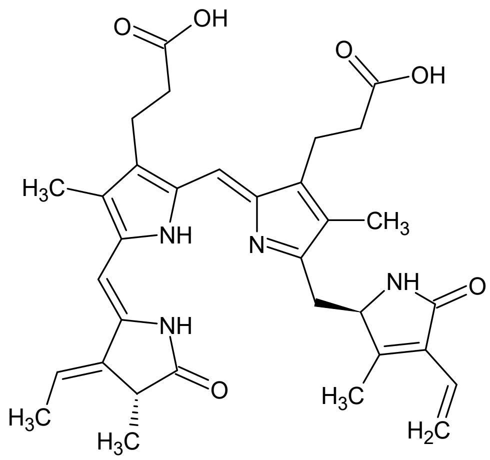

Fig.14. Idealised structure of Phycoerythrobilin

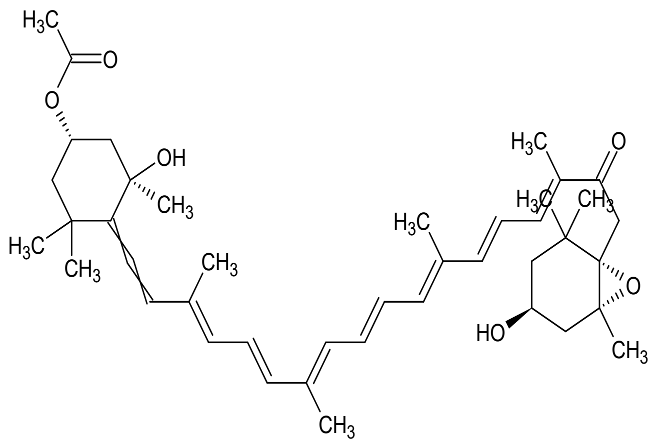

Fig.15. Idealised structure of fucoxanthin

Terpenoids

Terpenoids, a vast and diverse class of organic compounds, are abundantly present in various seaweed species and are recognized for their complex structures and a wide range of biological activities, including anti-inflammatory, antimicrobial, and anticancer effects. Their structural diversity, stemming from the iso-prenoid building blocks, allows for a variety of pharmacological interactions, contributing to their therapeutic potential[110]. For instance, certain di-terpenoids and tri-terpenoids isolated from brown and red algae have demonstrated significant cytotoxic effects against various cancer cell lines, often by inducing apoptosis or inhibiting cell proliferation [111]. Terpenoids found in seaweeds include halogenated monoterpene (Figure 16), di-terpenes, and sesquiterpenes. The uses of halogenated monoterpene are under investigation for their potential as antiviral and antimicrobial agents[31].

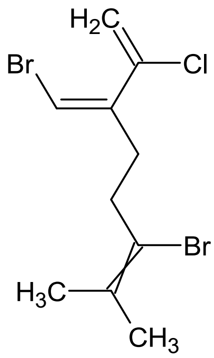

Fig. 16. Structure of halogenated monoterpene

DRUG DISCOVERY APPLICATIONS

The multifaceted bioactivities of seaweed-derived compounds underscore their immense promise for pharmaceutical development, particularly in addressing a range of health challenges from chronic diseases to infectious agents [112]. Marine compounds, such as carbohydrates, polyphenols, and peptides, exhibit antioxidant, anti-inflammatory, and anti-proliferative effects, making them valuable for nutraceuticals and pharmaceuticals [113]. This vast array of bioactive metabolites, including fatty acids, phycobiliproteins, polysaccharides, phenolic compounds, and carotenoids, positions algae as a remarkable biological resource for medical applications [10]. Algal metabolites, known for their diverse chemical compositions and physical properties, are increasingly recognized for their applications across pharmacological, nutraceutical, and microbiological sectors [114]. Their broad spectrum of biological activities makes them suitable for drug discovery, including the development of novel anti-melanoma agents [115]. The escalating incidence of melanoma globally, coupled with limitations of conventional therapies, necessitates the exploration of new therapeutic avenues, where seaweed-derived compounds offer a promising alternative [116].

Anti-Melanoma Effects

The distinctive chemical structures of algal metabolites, including their unique fatty acids, phycobiliproteins, polysaccharides, phenolic compounds, and carotenoids, confer potent pharmacological activities against various cancers, including melanoma [10]. For example, specific phlorotannins from brown algae have been shown to induce apoptosis and inhibit proliferation in melanoma cells through intrinsic and extrinsic pathways, demonstrating their targeted cytotoxic potential [117].

Additionally, some algal extracts have been observed to modulate signaling pathways crucial for melanoma progression, such as the MAPK/ERK and PI3K/Akt pathways, leading to suppressed tumor growth and metastasis [116]. Further studies indicate that certain algal peptides can sensitize melanoma cells to conventional chemotherapeutic agents, suggesting their utility as chemo sensitizers in combination therapies [118]. The anti-melanoma effects are further enhanced by the antioxidant and anti-inflammatory properties of these compounds, which can mitigate the oxidative stress and chronic inflammation often associated with cancer progression and treatment resistance [119]. These findings underscore the potential of seaweed-derived compounds as novel therapeutic agents for melanoma, either as standalone treatments or as adjuncts to existing regimens [120]. The complex interplay between various algal metabolites, including polysaccharides and polyphenols, contributes synergistically to their anticancer potential, offering a multifaceted approach to combating melanoma [121]. Beyond melanoma, the broader anticancer potential of algae-derived metabolites has been extensively explored, demonstrating efficacy against a wide range of cancer types [114]. Indeed, despite significant advancements in cancer treatment, global populations continue to face threats from this increasingly prevalent medical condition, necessitating the exploration of novel therapeutic avenues [114].

Marine algae, in particular, are gaining recognition as promising natural sources for anticancer agents due to their diverse array of bioactive compounds, which include polysaccharides, polyphenols, and peptides [122]. These compounds often modulate key cellular processes, including angiogenesis, apoptosis, and metastasis, making them attractive candidates for targeted cancer therapies [122]. For instance, low-molecular-weight fucoidan from brown seaweed has been shown to inhibit melanoma cell proliferation by modulating Bcl-2 phosphorylation and PTEN/AKT pathways [123].

Anticancer Potential

Similarly, other green algal extracts, such as those from Caulerpa racemosa, have demonstrated anti-proliferative effects against hepatocellular carcinoma, inhibiting tumor growth in experimental models [124]. These compounds from green seaweeds like Caulerpa racemosa not only exhibit anti-tumor properties but also possess anti-inflammatory effects that can mitigate aging-related disorders [124].

Moreover, these algal extracts from species such as Chlorella pyrenoidosa have been shown to induce apoptosis and necrosis in human liver cancer cells, leading to cellular changes such as membrane shrinkage and nuclear condensation [114]. Additionally, compounds isolated from various marine algae, including brown and blue-green species, have demonstrated significant potential as anticancer agents against prevalent forms of cancer, such as gastrointestinal cancers [125]. The inherent plasticity of these algal biopolymers further allows for extensive exploration into their potential anticancer actions on various cancerous signaling pathways, ultimately contributing to cancer reduction [114]. Further investigations into the molecular mechanisms reveal that these algal compounds can activate either caspase-dependent or caspase-independent apoptosis pathways, leading to the upregulation of tumor suppressor factors and down-regulation of specific cancer genes and signaling pathways [114]. This disruption of cellular pathways, combined with the induction of apoptosis, makes algal compounds highly attractive for developing novel therapeutic strategies [78]. These multifaceted actions, spanning cell cycle arrest, programmed cell death, and vascular disruption, highlight the broad therapeutic utility of algal metabolites in oncology [78].

Marine algal peptides, for instance, have demonstrated the ability to induce apoptosis, disrupt cell cycle progression, and inhibit angiogenesis, offering diverse anticancer mechanisms [126]. Eckol, for example, has been shown to inhibit the proliferation of SW1990 cells, while dieckol demonstrates anti-proliferative and anti-migratory effects on non-small-cell lung cancer by modulating the PI3K/AKT pathway [114].

Anti-inflammatory and Antioxidant Effects

Beyond their direct cytotoxic effects, many algal-derived compounds also exert significant anti-inflammatory and antioxidant activities, which indirectly contribute to their anticancer potential by mitigating oxidative stress and chronic inflammation that often promote tumour development and progression. These phytochemicals can activate the antioxidant defence system in normal cells, preventing reactive oxygen species-mediated genomic instability and aberrant cell proliferation while suppressing chemotherapy-induced oxidative stress.[127]

Furthermore, these antioxidants can act synergistically with chemotherapeutic agents to boost oxidative stress specifically in tumour cells, disable transcription factors, and activate apoptosis-related signaling pathways [108]. This dual action, promoting protective antioxidant effects in healthy cells while selectively increasing oxidative stress in cancer cells, highlights a sophisticated mechanism for therapeutic intervention [128]. The reduced toxicity and enhanced efficacy of algal-derived compounds compared to conventional chemotherapeutics make them particularly promising for cancer therapy, offering a less detrimental alternative to existing treatments [129].

Specifically, compounds such as phlorotannins found in brown algae exhibit potent antioxidant capabilities by scavenging free radicals and modulating inflammatory pathways, thereby impeding carcinogenesis [130]. This intrinsic ability to counteract oxidative stress and inflammation positions algal extracts as formidable candidates for both cancer prevention and adjuvant therapy [128].

Similarly, fucoxanthin, a carotenoid primarily from brown seaweeds, demonstrates significant antioxidant and anti-inflammatory properties, suggesting its potential in cancer therapy by targeting tumor cell hallmarks and potentially reducing drug resistance when combined with conventional treatments [131]. Other compounds, such as alginates and fucoidans, also contribute to the overall antioxidant and anti-inflammatory effects, further enhancing the therapeutic potential of algal extracts [132].

Neuroprotective Potential

Research also indicates that these protective agents derived from macroalgae, particularly phlorotannins, can counteract the harmful effects of radiotherapy and chemotherapy by inhibiting apoptosis and oxidative stress [114]. These protective properties extend to neurodegenerative conditions, where oxidative stress and inflammation are key pathological drivers, underscoring the broad therapeutic applicability of algal compounds beyond oncology [128]. This neuroprotective capacity stems from their ability to modulate signaling pathways associated with neuronal damage, offering a promising avenue for mitigating neurological side effects of cancer treatments [133].

Moreover, marine macroalgae polyphenols, including phlorotannins, have demonstrated significant neuroprotective properties through their potent antioxidant activity, offering potential therapeutic benefits for neurodegenerative diseases [134]. This makes them crucial in developing innovative neuroprotective drugs aimed at safeguarding neuronal cells from various forms of damage [134]. They achieve this by scavenging or suppressing the generation of reactive oxygen species, which are implicated in the progression of neurodegenerative diseases such as Alzheimer's and Parkinson's [134].

Furthermore, specific algal compounds like fucoxanthin and astaxanthin exhibit neuroprotective effects by inhibiting key enzymes involved in Alzheimer's disease pathology and suppressing amyloid-beta accumulation [135].

Additionally, other beneficial compounds found in algae, such as vitamins and phycobilins, contribute to these neuroprotective effects by modulating signaling pathways like NF-κB/Akt and MAPK, which regulate neuronal survival and prevent neurodegeneration [136]. This multifaceted neuroprotective action, spanning antioxidant, anti-inflammatory, and enzyme inhibitory effects, positions algal compounds as promising candidates for addressing complex neurodegenerative conditions and minimizing treatment-related neurotoxicity [137].

The diverse bioactive compounds present in marine algae have shown significant potential for therapeutic uses across various diseases, including neurodegenerative disorders [138]. These compounds act as neuroprotective agents by exhibiting antioxidant, anti-inflammatory, and anti-excitotoxicity properties and inhibiting enzymes and protein aggregation, all of which are critical mechanisms for managing neurodegenerative diseases [137].

Specifically, xanthines, bryostatin, and 11-dehydrosinulariolide have shown encouraging neuroprotective effects in various neurodegenerative disorders, such as Parkinson's and Alzheimer's diseases [139].

Antimicrobial Effects

The diverse chemical profiles of algal extracts also render them effective antimicrobial agents against a wide array of pathogenic microorganisms, including bacteria, fungi, and viruses [78]. This broad-spectrum activity is attributed to the presence of secondary metabolites such as polysaccharides, polyphenols, peptides, and fatty acids, which disrupt microbial cell integrity and inhibit essential enzymatic pathways [138].

Many algal bioactive compounds, such as phlorotannins and certain polysaccharides, have demonstrated potent antibacterial properties by interfering with bacterial cell wall synthesis and biofilm formation, thereby preventing microbial proliferation [111]. Moreover, certain microalgae produce biogenic compounds that exhibit significant antimicrobial activity against pathogenic bacteria, disrupting their growth and colonization [140].

For example, extracts from Ulva lactuca have shown inhibitory effects against both Gram-positive and Gram-negative bacteria, while compounds from Sargassum vulgare display antifungal activity against Candida albicans[35]. The efficacy of these algal compounds against drug-resistant strains of pathogens positions them as vital candidates for novel antimicrobial drug development [141]. This includes the disruption of quorum sensing mechanisms in bacteria, thereby hindering pathogenicity and biofilm formation, which are critical for chronic infections [54].

Moreover, the unique structural architecture of novel bioactive compounds from microalgal biomass may provide new avenues for anti-inflammatory activities, further broadening their potential applications beyond direct antimicrobial action [142]. This multifunctionality underscores the potential of algal extracts to address complex medical challenges by targeting multiple pathological pathways simultaneously [48]. Such diverse bioactivities of macroalgae-derived compounds are attracting considerable attention as sustainable and eco-friendly alternatives to conventional antimicrobial agents, which often face issues of toxicity and environmental concerns [143].

Specifically, marine algae and their derived compounds, including sulfated polysaccharides, carotenoids, lipids, fatty acids, and phlorotannins, possess promising anti-biofilm activities by inhibiting cell attachment, reducing growth, interfering with quorum sensing, and disrupting extracellular polymeric substances [144]. Furthermore, these algal extracts have demonstrated efficacy against multidrug-resistant bacterial strains, offering a promising avenue for combating the global challenge of antimicrobial resistance [140].

CHALLENGES AND FUTURE DIRECTIONS

Despite the promising therapeutic potential of algal extracts, significant challenges remain in their large-scale production, standardized extraction, and rigorous clinical validation, necessitating advanced biotechnological approaches and comprehensive regulatory frameworks. [145] For instance, optimizing cultivation conditions to enhance the biosynthesis of specific bioactive compounds within algae remains a critical area of research, and developing efficient and environmentally benign extraction methods that preserve their bioactivity and yield [119].

Furthermore, the complexity of algal extract compositions presents an ongoing challenge for precise characterization and quality control, thereby impeding consistent pharmacological evaluation and industrial application. [146] Addressing these complexities requires innovative analytical techniques, such as metabolomics, to accurately identify and quantify the diverse array of active compounds present in various algal species [147]. Moreover, robust in vitro and in vivo studies are essential to elucidate the mechanisms of action and confirm the efficacy and safety of these extracts, paving the way for their integration into pharmaceutical and nutraceutical industries [148].

Further research is warranted to explore the anti-biofilm activities of algal extracts, particularly against antibiotic-resistant strains, by investigating their ability to inhibit quorum-sensing pathways and disrupt extracellular polymeric substances [144]. Additionally, the identification of the specific anti-biofilm attributes of various microalgae and macroalgae extracts, including their pigments and other metabolites, is crucial for developing novel formulations, potentially in combination with materials like silver nanoparticles or dental composites [144]. Exploring innovative technologies for improving the use of algal biomass, such as advanced biorefinery concepts, is crucial for maximizing the yield of high-value compounds and ensuring economic viability in diverse applications [149].

However, the economic feasibility and practical application of microalgal biomass-derived high-value compounds on a large scale are hindered by substantial production costs and underdeveloped upstream and downstream processing technologies, encompassing cultivation systems, harvesting techniques, and extraction methods [150]. Overcoming these limitations requires a concerted effort in process intensification and the development of cost-effective, sustainable methodologies for isolating and purifying bioactive metabolites from microalgae [151]. These advancements will be critical for realizing the full potential of microalgae in contributing to a circular bioeconomy by providing sustainable sources for biofuels, bioplastics, and high-value bioproducts [152]. This necessitates a targeted research roadmap addressing multivariate strain engineering, hybrid cultivation architectures, and low-energy harvesting technologies to advance sustainable algal biorefineries [153]. Furthermore, novel approaches focusing on extremophilic microalgae, which thrive in harsh conditions, present promising avenues for producing specialized bioactive compounds with enhanced stability and unique therapeutic properties [154].

Table 1: Brown Algae

Algae Name	Source	Major Phytochemicals	Therapeutic Activities	Cosmeceutical Activities
Sargassum wightii	Indian coastal waters	Fucoidan, alginates	Anti-inflammatory, anti-diabetic	Anti-aging, anti-inflammatory, improves skin hydration
Fucus vesiculosus	Cold marine waters	Fucoxanthin, iodine	Thyroid regulation, anti-obesity	Anti-cellulite, anti-aging, skin toning
Laminaria japonica	Marine (Asia)	Laminarin, alginic acid	Antitumor, anticoagulant	Moisturizing, skin soothing, anti-wrinkle
Ecklonia cava	Marine (Korea/Japan)	Phlorotannins (eckol)	Neuroprotective, anti-aging	Anti-aging, anti-pigmentation, UV protection
Padinapavonica	Marine	Polyphenols, calcium	Anti-inflammatory, anti-osteoporotic	Skin firming, anti-aging, anti-elastase
Turbinariaornata	Tropical marine	Fucoxanthin, phenolics	Antioxidant, hepatoprotective	Antioxidant, anti-photoaging

Table 2: Green Algae

Algae Name	Source	Major Phytochemicals	Therapeutic Activities	Cosmeceutical Activities
Chlorella vulgaris	Freshwater	Chlorophyll, lutein	Detoxifying, anticancer, antioxidant	Skin detoxification, regeneration, brightening
Dunaliellasalina	Hypersaline marine	β-carotene, glycerol	Anti-aging, antioxidant, photoprotective	Photoprotection, improves skin elasticity, anti-aging
Haematococcuspluvialis	Freshwater	Astaxanthin	Strong antioxidant, cardioprotective, anti-aging	Potent anti-aging, reduces wrinkles, UV protection
Ulva lactuca	Coastal marine	Ulvan, sulfated polysaccharides	Antiviral, antioxidant, wound healing	Moisturizing, wound healing, skin barrier repair
Codium fragile	Marine	Sulfated polysaccharides	Immunostimulatory, antioxidant	Skin firming, antioxidant protection

Table 3: Red Algae

Algae Name	Source	Major Phytochemicals	Therapeutic Activities	Cosmeceutical Activities
Gracilaria verrucosa	Tropical marine	Agar, galactans	Antiviral, antimicrobial	Skin hydration, film-forming agent
Kappaphycusalvarezii	Tropical marine (India)	Carrageenan	Antiviral, anticoagulant	Moisturizing, thickening, stabilizer
Porphyra umbilicalis	Intertidal zones	Porphyran, amino acids	Anti-inflammatory, antioxidant	Anti-aging, skin protection
Palmariapalmata	Cold marine waters	Proteins, vitamins	Nutraceutical, antioxidant	Skin nourishment, antioxidant

Table 4: Blue-Green algae

Algae Name	Source	Major Compounds	Therapeutic Activities	Cosmeceutical Activities
Spirulina platensis	Freshwater & marine	Phycocyanin, proteins, vitamins, amino acids	Antioxidant, anti-inflammatory, immunomodulatory	Skin nourishment, anti-aging, soothing
Anabaena spp.	Freshwater, symbiotic (Azolla)	Phycocyanin, phenolics, alkaloids	Antioxidant, antimicrobial	Skin protection, anti-aging
Aphanizomenonflos-aquae	Freshwater lakes	Phycocyanin, amino acids, minerals	Antioxidant, neuroprotective, immune booster	Skin rejuvenation, detoxifying
Oscillatoria spp.	Freshwater & marine	Phenolics, fatty acids, pigments	Antimicrobial, anti-inflammatory	Anti-acne, skin cleansing
Lyngbya spp.	Marine & freshwater	Lipopeptides, fatty acids	Antimicrobial, anticancer	Antimicrobial skincare
Phormidium spp.	Freshwater, hot springs	Phycocyanin, carotenoids	Antioxidant, antibacterial	Anti-aging, skin conditioning
Gloeocapsa spp.	Rocks, soil (terrestrial)	Polysaccharides, UV-protective pigments	Antioxidant	UV protection, hydration
Synechococcus spp.	Marine & freshwater	Carotenoids, phycobiliproteins	Antioxidant, anti-inflammatory	Skin brightening, anti-aging

Table 5: Golden Algae

Algae Name	Source	Major Phytochemicals	Therapeutic Activities	Cosmeceutical Activities
Isochrysisgalbana	Marine	DHA, fucoxanthin	Cardio protective, anti-inflammatory	Skin hydration, anti-aging
Ochromonas spp.	Freshwater & marine	Carotenoids, lipids	Antioxidant	Skin protection, anti-aging
Dinobryon spp.	Freshwater	Xanthophylls, lipids	Antioxidant	Skin conditioning
Synura spp.	Freshwater	Silica scales, carotenoids	Antioxidant	Skin protection
Mallomonas spp.	Freshwater	Silica, carotenoids	Antioxidant	Skin detox support
Chrysococcus spp.	Freshwater	Carotenoids	Antioxidant	Skin protection
Chromulina spp.	Freshwater & marine	Lipids, pigments	Anti-inflammatory	Skin nourishment
Uroglena spp.	Freshwater	Lipids, carotenoids	Antioxidant	Skin conditioning
Tisochrysislutea	Marine (diatom)	Fucoxanthin, EPA, carotenoids	Antioxidant, anti-inflammatory, cardioprotective	Anti-aging, skin protection, UV protection

CONCLUSION

This review highlights the incredible pharmacological potential of algal extracts. From fighting hyperpigmentation to serving as powerful antimicrobial and antioxidant agents, algae are clearly a vital source of new bioactive compounds. These findings underscore the need to continue exploring both macroalgae and microalgae as sustainable, high-value resources for the pharmaceutical, cosmetic, and food industries.

To move forward, the focus should shift toward refining extraction methods and establishing standardized protocols. This will ensure that these natural products remain effective and safe for consistent use. Furthermore, fitting algal production into a circular economy framework will boost both its sustainability and economic appeal. While scaling up production and managing costs remain significant hurdles, they are challenges worth overcoming to see these compounds used more widely.

Investing in advanced biorefineries and genetic engineering will be key to unlocking the full potential of algae to address global health and environmental issues. Techniques like metabolic engineering and gene editing allow for precise control over how these organisms produce valuable compounds, helping us move from small-scale lab success to full-scale industrial production. As we continue to advance in synthetic biology and bioinformatics, the discovery and optimization of new algal molecules will only accelerate.

Ultimately, these biotechnological strides can transform algae into sustainable bio-factories. By adopting integrated biorefinery concepts, where every part of the biomass is used, we can maximize economic returns while minimizing waste. Microalgae, in particular, offer a unique advantage: they grow rapidly, can thrive in harsh environments where other crops cannot, and can produce everything from medical therapeutics to biofuels. By improving how we cultivate and process these organisms, we can overcome initial costs and fully embrace the benefits of a greener, algal-based bio-economy.

ABBREVIATIONS

NF-kB: Nuclear factor kappa B, MAPK-Mitogen activated protein kinase, Nrf2- Nuclear factor erythroid 2-related factor 2, ROS- Reactive oxygen species, UV-Ultraviolet, DHA: Docosahexaenoic Acid, EPA: Eicosapentaenoic Acid , MAAs: Mycosporine-like Amino Acids, PI3K- Phosphoinositide 3-kinase, AKT- Protein kinase B, PTEN- Phosphatase and tensin homolog, ERK- Extracellular signal regulated kinase, Bcl-2 – B-cell lymphoma 2, SW1990- Human pancreatic cancer cell line, DNA- Deoxyribonucleic acid, RNA- Ribonucleic acid.

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