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Review

Cosmeceutical Significance of Seaweed: A Focus on Carbohydrates and Peptides in Skin Applications

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Abstract: The term 'cosmeceutical' refers to cosmetic products that offer medicinal or drug-like benefits. Marine algae are rich sources of bioactive compounds, particularly carbohydrates and peptides, which have gained attention for their potential in cosmeceuticals. These compounds are abundant, safe, and have minimal cytotoxicity effects. They offer various benefits to the skin, including addressing rashes, pigmentation, aging, and cancer. Additionally, they exhibit properties such as antimicrobial, skin-whitening, anti-aging, antioxidant, and anti-melanogenic effects. This review surveys the literature on the cosmeceutical potentials of algae-derived compounds, focusing on their roles in skin whitening, anti-aging, anticancer, antioxidant, anti-inflammatory, and antimicrobial applications. The discussion also includes current challenges and future opportunities for using algae for cosmeceutical purposes.

Keywords: cosmeceuticals; marine algae; bioactive compounds; skin health; skincare innovations

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1. Introduction

Cosmeceutical ingredients are active compounds utilized to enhance the appearance and health of the human body, representing a hybrid category positioned between cosmetics and pharmaceuticals. Cosmeceutical formulations aim to improve skin health and beauty [1–3]. They combine cosmetic products with bioactive molecules, offering medicinal or drug-like applications to improve skin health and texture [4,5]. With the growing emphasis on skincare and modernization, cosmetic companies are expanding globally each year. To meet customer demands, these companies are increasingly relying on synthetic cosmetics and constituents. However, the ineffectiveness of synthetic components poses risks as they can accumulate in the skin, potentially causing toxic effects and harm to the skin's structure. For instance, hydroxybenzoic acid esters (parabens), widely used in cosmetic formulations, have been linked to adverse effects on the skin and an increased incidence of malignant melanoma and breast cancer [6]. Globally, the cosmeceutical sector experiences annual growth driven by evolving beauty trends.

In response to consumer preferences, industries are increasingly relying on synthetic cosmetic ingredients such as hydroquinone (HQ), phthalates, para-aminobenzoic acid (PABA), benzophenones, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), and dibenzoylmethane (DBM) in formulations. The Scientific Committee on

Consumer Safety warns that the excessive use of synthetic ingredients in cosmeceutical formulations may result in various toxicities, including acute toxicity, corrosion, irritation, dermal absorption, repeated dose toxicity, reproductive toxicity, mutagenicity/genotoxicity, carcinogenicity, and photoinduced toxicity on the skin and human health. For example, hydroxyanisole, commonly found in skin-whitening creams, has been associated with harmful effects such as ochronosis and potential mutagenicity [7–9]. Phthalates, another common substance in cosmetic formulations, have been linked to DNA mutations and damage in human male gametes [10,11]. Moreover, synthetic chemical compounds can have detrimental effects on animals, including reduced sperm counts, altered pregnancy outcomes, and congenital disabilities in male genitalia [12].

Consequently, consumers are shifting towards natural cosmetic products [13]. This growing demand for skincare formulations and the search for alternative natural ingredients have led to the production of various types of cosmeceutical skin products [14]. Throughout history, cosmetics have played a significant role in society, traditionally utilizing natural compounds extracted from milk, flowers, fruits, seeds, vegetables, herbs, marine algae, and minerals [15]. Some regions still utilize marine macroalgae as a sustainable natural remedy, incorporating it into skincare products [16]. Cosmetic products serve as both cleaning and beautifying agents, aiming to enhance the user's aesthetics without causing harmful side effects. Many products, including creams, lotions, and ointments, contain bioactive molecules such as vitamins, minerals, and antioxidants that promote skin, nail, and hair health [17–19].

This review aims to analyze the potential of two major seaweed components as natural ingredients in cosmetics that substitute synthetic compounds to promote more eco-friendly solutions.

2. Natural Cosmetic Products

The cosmetic products can come in various forms, ranging from simple creams or lotions to edible options like pills or functional foods with cosmeceutical activity [20,21]. However, while they cannot claim a genuine therapeutic function, it's crucial to differentiate them from cosmetic preparations that target skin disease prevention. For instance, sunscreen is considered a drug for preventing skin diseases caused by solar exposure [20,21]. To accommodate cosmetic products claiming biological action, the term "cosmeceutical" was coined and is now widely used across countless products [22,23]. As discussed earlier, the cosmetic industry has long relied on synthetic ingredients. However, various factors, including modern lifestyle changes and the shortcomings of synthetic cosmetics, such as low absorption rates or harmful side effects, have spurred a shift towards natural bioactive compounds [24]. Consider parabens (hydroxybenzoic acid esters), extensively used in synthetic cosmetic products, which mimic the female hormone estrogen. However, this mimicry could potentially increase the risk of developing malignant melanoma or breast cancer [25,26]. Another example is phthalate, a compound commonly used in plastic production and found in several cosmetic products like nail polish, which has been shown to cause DNA modification and damage in human sperm cells [27].

In essence, understanding skin growth and damage mechanisms, coupled with the successful utilization of natural products as solutions to the aforementioned issues, has underscored the benefits of adopting a cosmeceutical approach to cosmetics rather than purely aesthetic ones [28]. Cosmetics have held a central role in human society since ancient times, primarily for religious and ornamental purposes. In antiquity, these products were derived from natural compounds like milk, flowers, fruits, seeds, and vegetables, as well as minerals like clay and ash [29]. In certain regions, seaweed is utilized as an alternative remedy for skin-related ailments, making it an incredible natural raw material for cosmetics [29,30]. The bioactive compounds found in seaweed possess multiple activities, making them valuable as active ingredients in cosmetic formulations [31–33].

Synthetic Cautions: A Road to the Natural Ingredients

According to Fernández-Álvarez et al. [34] and Knowland et al. [35], benzophenones, DBM, and PABA have exhibited allergic phototoxicities, dermatitis, and skin irritations. Similarly, BHA and BHT, commonly found in moisturizers and lipsticks, have been associated with allergic reactions, irritation, and skin corrosivity. Parabens, another ingredient, have been linked to carcinogenic and neurotoxic effects, among other harmful health consequences. Despite their widespread use in cosmetic formulations, parabens pose a high risk of breast cancer and the development of malignant melanoma in women [36]. However, the ACDS Contact Allergen Management Program (CAMP) report suggests that while around 19% of products contain different types of parabens, mainly methylparaben, ethylparaben, propylparaben, and butylparaben, these components exhibit little allergenicity compared to other preservatives, with minimal adverse reactions and low toxicity, ensuring safety and cost-effectiveness [37].

Hafeez and Maibach [38] reported fewer sensitizing effects of parabens in commercial applications, with limited reports often attributed to their use on damaged skin. Polyethylene glycol (PEG) is identified as a genotoxic compound that can cause skin irritation, systemic toxicities, and skin damage. In skin cosmetics, PEGs serve as emollients, emulsifiers, and vehicles, aiding in softening and lubricating the skin, proper mixing of water-based and oil-based ingredients, and delivering ingredients deeper into the skin. Additionally, the Agency for Toxic Substances and Disease Registry (ATSDR) and the Centers for Disease Control and Prevention (CDC) highlighted the toxicity of dibutyl phthalate (DBP), which can lead to DNA damage in male reproductive cells [39].

Previous studies by Khan and Alam [40] and Warbanski [41] have reported harmful effects of cosmetic ingredients in animal studies, including male genitalia disabilities, altered pregnancy outcomes, and reduced sperm counts. Moreover, the EC 1223/2009 regulation advocates for the prohibition of testing finished cosmetic products on animals and their marketing. To address the toxicities associated with these formulations, consumers have increasingly favored natural skincare products in recent years. Consequently, industries are shifting towards natural bioactive ingredients sourced from various natural resources, which are eco-friendly and less toxic [42,43]. Additionally, studies by Kim et al. [44], Pereira [45], Maqsood, Benjakul, and Shahidi [46], Panzella and Napolitano [47], and de Jesus Raposo et al. [48] suggest that a wide range of natural resources, including terrestrial plants, fungi, marine algae, bacteria, and animals, can be utilized in skin cosmetic products.

3. Introduction to Seaweeds

Marine macroalgae, commonly referred to as seaweed, have garnered significant attention for their skincare benefits. These organisms, which are eukaryotic and photosynthetic, thrive in aquatic environments along coastlines and in seawater. Classified into three primary taxonomic groups—red algae, brown algae, and green algae—marine macroalgae belong to the Rhodophyta, Ochrophyta, and Chlorophyta phyla, respectively [49–52]. Seaweeds are macroscopic, multicellular organisms with the ability to perform photosynthesis, thanks to chlorophyll and other pigments. They are widespread in coastal regions, including intertidal and sub-tidal zones, as well as in brackish water [53]. Brown algae, red algae, and green algae are categorized based on their pigment composition, with brown algae belonging to the Chromista kingdom and green and red algae to the Plantae kingdom [54,55]. Seaweeds boast a rich diversity of bioactive compounds, surpassing those found in terrestrial organisms [56–58].

The cosmetic and cosmeceutical industries are increasingly turning to macroalgae-derived compounds due to their promising biological activities [59–61]. Thus, seaweed compounds, such as lipids, fatty acids, polysaccharides, vitamins, minerals, amino acids, phenolic compounds, proteins, and pigments, have attracted attention for their potential skincare benefits [62–64]. Utilization of seaweed biomass in skincare formulations depends on their specific constituents, such as polysaccharides, carbohydrates, proteins, peptides, amino acids, phenolic compounds, vitamins, minerals, fatty acids, and pigments [31,65]. These bioactive constituents offer a range of benefits for the skin, including anti-tumor, anti-allergic, antimicrobial, antioxidant, anti-inflammatory, antilipidemic, antiwrinkle, anti-aging, moisturizing, and photoprotective properties [66–70]. Driven by consumer demand for natural skincare solutions, the cosmetic industry is increasingly incorporating marine macroalgae into its products. With their diverse array of bioactive compounds and proven skincare benefits, seaweeds are becoming valued ingredients in the pursuit of healthier, more radiant skin.

Seaweeds: Interesting Metabolites

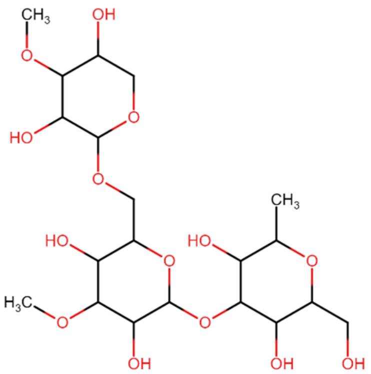
Seaweed-derived metabolites exhibit significant potential for application in cosmeceutical products owing to their diverse bioactive constituents and associated biological activities [71]. Polysaccharides, in particular, play pivotal roles in cosmetics, serving functions such as moisturization, emulsification, wound healing, and thickening [72]. In a study by Fernando et al. [73], fucoidan extracted from *Chnoospora minima* (Phaeophyceae) demonstrated anti-inflammatory properties. This compound inhibited nitric oxide production induced by lipopolysaccharides and reduced levels of inducible nitric oxide, cyclooxygenase-2, and prostaglandin E2 in RAW macrophages. Similarly, Ariede et al. [74], Wang et al. [75], and Teas and Irhimeh [76] reported diverse beneficial effects of polysaccharides derived from *Fucus vesiculosus* (Phaeophyceae), including anti-aging, anti-melanogenic, anti-cancer, and antioxidant activities. These effects were attributed to the stimulation of collagen production, inhibition of tyrosinase, reduction of melanoma growth, and prevention of oxidation, respectively. Moreover, Ghorbanzadeh et al. [77] demonstrated the anti-inflammatory activity of sulfated polysaccharides from *Padina tetrastromatica* (Phaeophyceae) through inhibition of COX-2 and iNOS in a rat model of Paw edema. Khan et al. [78] reported the anti-inflammatory effects of polyunsaturated fatty acids isolated from *Undaria pinnatifida* (Phaeophyceae) on mouse ear edema and erythema. Additionally, Vasconcelos et al. [79] and Santos et al. [80] explored the antioxidant potential of methanolic extracts from *Osmundaria obtusilo* and *Palisada flagellifera* (Rhodophyta) using various assays, including DPPH, ABTS, metal chelating, Folin ciocalteau, and β-carotene bleaching assays.

Sargachromanol E, a phenolic compound extracted from *Sargassum horneri* (Phaeophyceae), demonstrated anti-aging effects by inhibiting matrix metalloprotein expression in UVA-irradiated dermal fibroblasts [81]. Similarly, Lee et al. [82] investigated the anti-melanogenic activity of Sargachromanol E from *Sargassum serratifolium* (Phaeophyceae), observing the downregulation of microphthalmia-associated transcription factors in B16F10 melanoma cells. Yoon et al. [83] also reported anti-melanogenic activity, showing inhibition of tyrosinase and melanin expression in the ethanolic extract of the brown macroalgae *Petalonia binghamiae*.

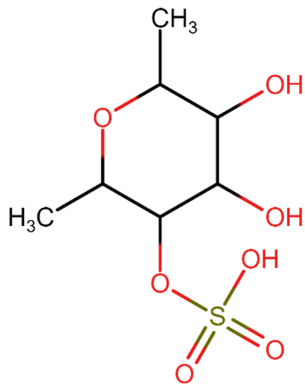
Furthermore, Wang et al. [84] found collagenase inhibition and control of matrix metalloproteinase (MMP) expression in vitro with mycosporine amino acids (MAAs) derived from *Porphyra* sp. (Rhodophyta). *Pyropia yezoensis* (formerly *Porphyra yezoensis*) (Rhodophyta)-derived mycosporine amino acids exhibited antioxidant activity through ROS scavenging potential and MMP expression modulation in human skin fibroblasts [85]. Hartmann et al. [86] identified anti-aging properties through collagenase inhibition with MAAs derived from *Palmaria palmata* (Rhodophyta). Moreover, certain macroalgae species, such as *Laurencia pacifica*, *Palisada rigida* (formerly *Laurencia rigida*), *Wilsonosiphonia howei* (formerly *Polysiphonia howei*), *Rhodomela confervoides*, and *Schizymenia dubyi* (Rhodophyta), were identified as rich sources of phenolic compounds [87,88].

4. Seaweed-Derived Polysaccharides for Skin Benefits

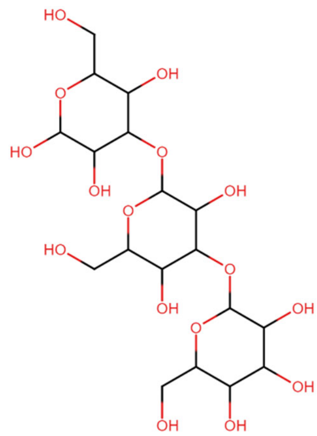
Polysaccharides derived from marine macroalgae are renowned for their myriad biological benefits. Various research studies have highlighted the presence of polysaccharides such as ulvan, fucoidan, alginate, laminarin, carrageenan, sulfated polysaccharides, agar, and agarose in macroalgae, emphasizing their potential cosmeceutical advantages. Berthon et al. [19] underscored the diverse bioactivities of fucoidan, including antioxidant, antimicrobial, anti-inflammatory, anticancer, and antihyperlipidemic properties. Venkatesan et al. [89] proposed the utilization of polysaccharides as bioactive constituents in skincare formulations, where they play pivotal roles as moisturizers, emulsifiers, wound healers, and thickeners. Previous studies, such as those by Yu and Sun [90], have demonstrated the inhibitory effects of fucoidan obtained from brown algae like *Fucus* sp. and *Sargassum* sp., as well as brown alga *Laminaria* sp. (Phaeophyceae), on tyrosinase activity. Polysaccharides are regarded as the most significant and beneficial compounds present in macroalgae, prized for their skin beneficial activities. Seaweeds boast a plethora of polysaccharides, including chitin, fucoidans, agar, carrageenan, alginates, ulvans, terpenoids, and tocopherol. In skincare cosmeceuticals, marine algae have shown promising activities such as anti-melanogenesis, antioxidant, anti-skin-aging, anti-inflammation, anti-atopic dermatitis, anti-skin-cancer, and repair of UV-induced damage. However, their potential depends on their chemical and biochemical properties [89,91–114]. The chemical structures of seaweed-derived polysaccharides depicted below in Figure 1.



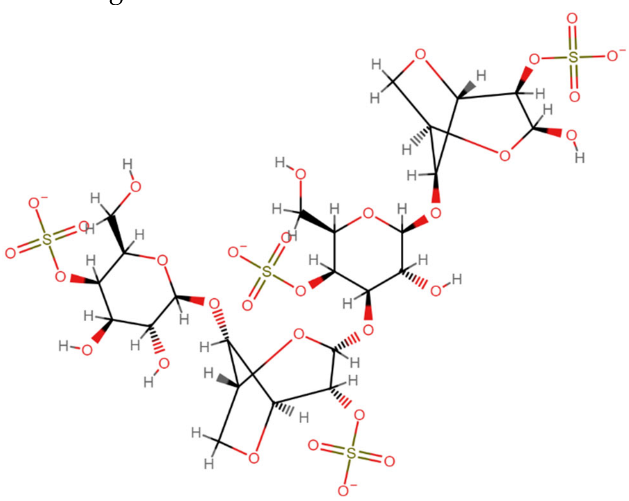
Arabinogalactan



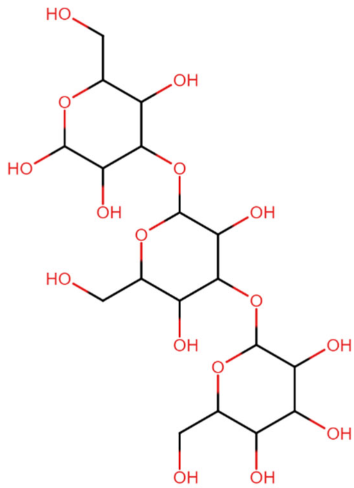
Fucoidan



beta-(1-3)-galactotriose



iota-carrageenans



Laminaran

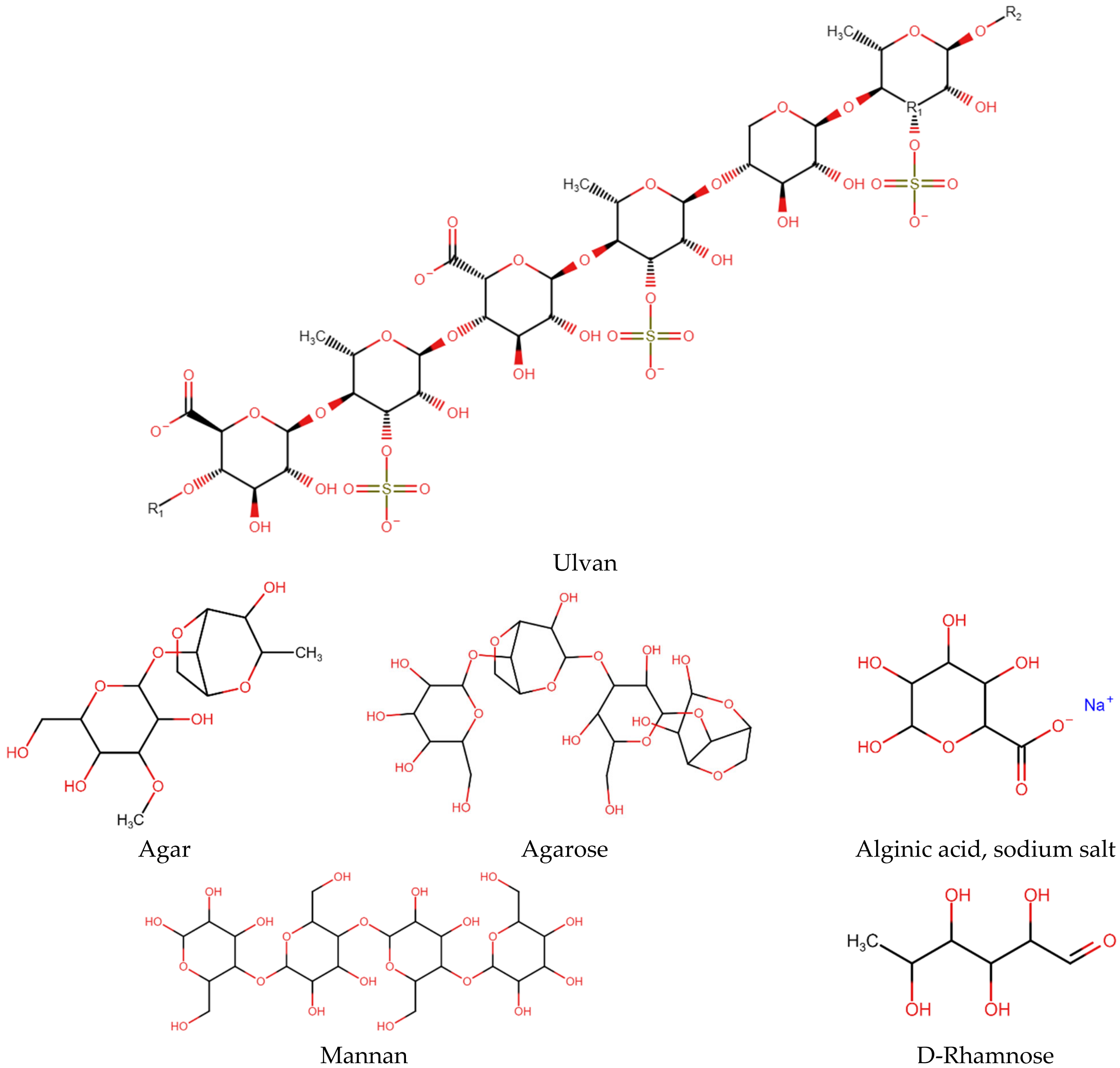


Figure 1. Structural analysis of polysaccharide compounds isolated from seaweeds.

Numerous macroalgal species, including *Kappaphycus alvarezii* (formerly *Eucheuma cottonii*) (Rhodophyta), *Sargassum polycystum* (Phaeophyceae), *Padina boryana* (formerly *Padina tenuis*) (Phaeophyceae), *Fucus vesiculosus* (Phaeophyceae), and *Porphyra umbilicalis* (Rhodophyta), are rich sources of carbohydrates. Polysaccharides find wide-ranging applications in skincare products, including photoprotection, moisturization, wound healing, thickening, emulsification, and preservation. Presently, skincare product manufacturers focus on compounds capable of regulating tyrosinase inhibition, collagenase and elastase inhibition, reduction of matrix metalloproteinase (MMP) activity, reactive oxygen species (ROS) reduction, and antioxidant activity. Holtkamp et al. [115] highlighted the multifaceted benefits of fucoidan, particularly in skin protection, antioxidants, antiaging, antiviral, anti-inflammatory, antitumor, and anticoagulant properties, supported by epidemiological and experimental studies. Fujimura et al. [116] demonstrated a significant reduction in skin thickness and improved elasticity with the application of a gel formulation containing 1% fucus extract. Additionally, Kakita and Kamishima [117] explored the use of fucoidan in topical anti-inflammatory formulations for cosmetic after-sun damage, allergic condition soothing products, and post-surgical formulations. Polysaccharides have also been widely acknowledged for their antioxidant, antiviral, anticoagulant, and antitumor properties in commercial skincare products. Park and Choi [118] demonstrated enhanced inhibition of melanoma cells with low-molecular-weight fucoidan. Polysaccharides play a crucial role in inhibiting collagenase and elastase. Sulfated polysaccharides from the brown alga *Sargassum fusiforme* (formerly *Hizikia fusiformis*) (Phaeophyceae) exhibited potential inhibition of collagenase and elastase pathways in UVB-exposed HDF cells [119]. Fucoidan derived from *Chnoospora minima* and *Sargassum polycystum* showed dose-dependent inhibition of elastase and collagenase activities [120]. Additionally, Moon et al. [121] and Yu et al. [122] investigated the inhibitory effect of fucoidan on the MMP1 promoter and its ability to increase Type-1 procollagen synthesis. Polysaccharides possess excellent water-retention properties, making them effective humectants and moisturizers in cosmetic formulations. Research by Huang et al. [123] highlighted the superior hydration and moisturizing effects of polysaccharides from *Saccharina japonica* (formerly *Laminaria japonica*) (Phaeophyceae) compared to hyaluronic acid. Sulfated polysaccharides isolated from the green macroalgae *Ulva linza* (formerly *Ulva fasciata*) exhibited superior moisture absorption and retention over 96 h compared to glycerol [124]. Polysaccharides from *Saccharina japonica*, *Pyropia haitanensis* (formerly *Porphyra haitanensis*) (Rhodophyta), *Codium fragile*, *Ulva linza* (formerly *Enteromorpha linza*), and *Bryopsis plumosa* (Chlorophyta) also displayed significant moisture absorption and retention capabilities [125]. The moisture-holding capacity was influenced by factors such as sulfate content and molecular weight. An oligosaccharide zinc complex from *Laminaria digitata* (Phaeophyceae) exhibited anti-acne activity by reducing sebum production [126]. Sebaaly et al. [127] reported the bactericidal activity of sulfated galactan derived from *Corallina* sp. (Rhodophyta) against *Enterococcus faecalis* and *Streptococcus epidermidis*. Alginates have been utilized in cosmetics for face masks and body wash ingredients due to their beneficial effects on skin structure and function, particularly in solidifying and stabilizing emulsions at low pH levels [128,129]. Balboa et al. [74] proposed agar's versatile use in creams, serving as an emulsifier, stabilizer, moisturizer, and component in various cosmetic products like lotions, deodorants, anti-aging treatments, exfoliants, and acne treatments. This thematic is also discussed largely in the literature [130–134]. Alginic acid, derived from various brown algal species such as Fucales and Laminariales, *Ascophyllum* sp., *Durvillaea* sp., *Ecklonia* sp., *Laminaria* sp., *Macrocystis* sp., *Saccharina* sp., *Sargassum* sp., and *Turbinaria* sp., has been highlighted for its potential applications by Hempel, Colepicolo, and Zambotti-Villela et al. [135], particularly in skin-protective or barrier creams for dermatitis treatment, as well as in beauty masks or facial packs.

Furthermore, Kappa-, Iota-, and Lambda-carrageenan, extracted from different carrageenophytes like *Betaphycus gelatinus*, *Chondrus crispus*, *Eucheuma denticulatum*, *Gigartina* sp., *Kappaphycus alvarezii*, *Hypnea musciformis*, *Mastocarpus* sp., and *Mazzaella* sp., from the Rhodophyta, find usage in cosmetology for various purposes such as lotions, sunscreens, medicines, deodorant sticks, sprays, and foams [136–138]. Porphyrin, a sulfated polysaccharide obtained from the aqueous extract of red algae *Porphyra* sp. and *Bangia* sp. [49,139], has demonstrated potential cosmeceutical applications including skin-whitening, antiulcer, analgesic, and anti-inflammatory properties. Various brown seaweed species like *Laminaria* sp., *Saccharina* sp., *Ascophyllum* sp., *Fucus* sp., *Sargassum* sp., and *Undaria* sp. are recognized for their laminaran properties, associated with antitumor, anti-inflammatory, antiviral, antioxidant, anticoagulant, and anti-cellulite properties [24,140,141]. Among these, sulfated polysaccharides have garnered significant attention in cosmeceutical applications, exhibiting properties such as UV protection, anti-inflammatory, anticoagulant, antithrombotic, tyrosinase inhibition, antitumoral, antibacterial, antidiabetic, and antioxidative effects [142–144]. Na et al. [145] elucidated the role of fucoidan in inhibiting matrix metalloproteinase induced by UVB radiation.

According to Senni et al. [146], fucoidan shows promise in preventing photoaging of the skin. Additionally, it acts as a tyrosinase inhibitor, reducing skin pigmentation when utilized in skin-whitening formulations [147,148]. Ulvan, as suggested by Carvalho and Pereira [149], is considered a desirable raw material for cosmeceuticals due to its beneficial moisturizing, protective, antitumor, and antioxidative properties, particularly in gel formulations [150,151]. Polysaccharides constitute approximately 60% of all active metabolites found in seaweed. Composed of various monosaccharides linked by glycosidic bonds, these compounds form long-chained carbohydrates with hydrophilic and water-soluble properties, possessing a regular structure [152]. Serving a structural role in seaweed cell walls and acting as an energetic reservoir, polysaccharides exhibit proven biological activities and can be utilized in cosmeceutical products as moisturizers and antioxidants [153]. Among polysaccharides, macroalgal hydrocolloids, known as phycocolloids, hold significant industrial value. These structural polysaccharides, found in seaweed, typically form colloidal solutions—an intermediate phase between a solution and a suspension. As such, polysaccharides find applications across various industries, particularly in cosmetics, serving as thickeners, gelling agents, and stabilizers for suspensions and emulsions [152]. Table 1 below tabulates seaweed-derived compounds and their skin-beneficial actions.

Table 1. Biological activities and properties of seaweed-derived polysaccharide compounds in skincare.

Seaweed/s	Compound	Properties/Activities	References
Ulva pertusa, *Ulva* sp.	**Ulvan**	Antiaging, antiherpetic	[153,154]
Saccharina japonica, *Chondrus crispus*, *Codium tomentosum*	**Polysaccharides**	Hydration	[155]
Saccharina longicruris, *Laminarin (Sigma)*	**Laminaran**	Reconstructed dermis; skin cell anti-inflammation; antioxidant	[156,157]
Ascophyllum nodosum, *Chnoospora minima*, *Ecklonia maxima*, *Hizikia fusiforme*, *Saccharina japonica*, *Sargassum hemiphyllum*, *Sargassum horneri*, *Sargassum polycystum*, *Sargassum vachellianum*	**Fucoidans**	Photoaging inhibition; minimized elastase activity; antioxidant, anti-inflammatory; collagenase and elastase inhibition; skin-whitening	[158–168]
Red seaweeds, *Porphyra haitanensis*, *Gracilaria chouae*, *Gracilaria blodgettii*	**Carrageenans**	Antioxidant, antitumor, antiaging, thickening properties, radiation protection	[169–175]
Brown seaweeds	**Alginate**	High stability, thickening agent, gelling agent	[176–178]
Pterocladia, *Pterocladiella*, *Gelidium amansii*, *Gracilaria*	**Agar**	Thickener; antioxidant	[179–181]

4.1. Agar

Agar, also known as agar-agar or agarose, is a powerful gelatinous hydrocolloid extracted from various species of red seaweed. It comprises a heterogeneous mixture of two carbohydrates, agarose and agaropectin, which are distributed within the cell wall and intercellular spaces, serving as structural carbohydrates [182]. Agarose, constituting 50–90% of agar, primarily imparts its gelling properties [183,184]. This polysaccharide, characterized by its high molecular weight, consists of multiple (1–3)-β-D-galactopyranosyl-(1–4)-3,6-anhydro-α-L-galactopyranose units. However, modifications to this molecule's structure are observed due to factors such as seaweed species and variations in biotic and abiotic parameters [185]. Agaropectin, present in smaller quantities, is a heterogeneous mixture of α-1,3-linked D-galactose containing sulfate and pyruvate moieties. The gelling properties of agar depend on the degree of sulfation and the concentration of 3,6-anhydrogalactose [186,187]. Beyond its gelling properties, agar is utilized as an emulsifier and stabilizer in creams and regulates moisture content in cosmetic products, including hand lotions, liquid soap, deodorants, foundation, exfoliants, cleansers, shaving creams, and facial moisturizers/lotions, as well as in treatments for acne and aging [188]. Agar exhibits high-temperature tolerance (up to 250 °C) and retains its characteristics even at near-boiling temperatures, making it suitable for applications in jellied confections, where ingredients can be treated at high temperatures and subsequently cooled [189]. Additionally, there may be other bioactivities associated with the sulfated-galactan present in agar [190,191].

Agar applications in pharmaceuticals and industrial cosmetics include use as a thickener and as an ingredient for tablets or capsules for drug delivery [192,193]. Carrageenans, approved for food applications and generally recognized as safe (GRAS), are high-molecular-weight sulfated linear polysaccharides with a backbone of alternating 3-D-galactopyranose and 4-D-galactopyranose with anhydrogalactose residues [137,194–198]. Porphyran, a complex sulfated galactan found in *Porphyra* sp., exhibits therapeutic properties such as anti-allergic effects, tyrosinase inhibition, protection against ultraviolet B radiation, anti-inflammatory and antitumoral activity, and promotion of beneficial bacteria growth in the intestinal microbiota without toxicity in mouse models [199–205].

4.2. Alginic Acid

Alginic acid is the primary polysaccharide found in many brown seaweeds, including species such as *Ascophyllum*, *Durvillaea*, *Ecklonia*, *Laminaria*, *Lessonia*, *Macrocystis*, *Saccharina*, *Sargassum*, and *Turbinaria*. It is a linear copolymer of β-D-mannuronic acid and α-L-guluronic acid units linked by 1,4-glycosidic bonds. The extraction process involves converting an insoluble mixture of alginic acid salts into soluble salts, known as alginate or algin, which can be extracted in aqueous solutions [206,207]. In the presence of divalent cations such as Mg^{2+}, Ca^{2+}, Sr^{2+}, and Ba^{2+}, alginates readily form hydrogels. Extraction involves converting insoluble alginic acid and its salts into water-soluble potassium and sodium alginate. The stiffness or viscosity of these gels depends on the structural properties of the polymers (the amount of α-L-guluronate residues) and is influenced by the amount of external salt present [208,209]. Furthermore, under acidic conditions, alginic acid becomes insoluble, forming gels with its sodium and potassium salts, while still retaining water-soluble properties [210]. Alginates find widespread use as gelling agents, thickeners, protective colloids, or emulsion stabilizers in various cosmetic formulations, including hand jellies, lotions, ointment bases, pomades, hair preparations, greaseless creams, dentifrices, and other cosmetic products, owing to their chelating properties. This polysaccharide can also be employed in the formulation of skin protectants to prevent industrial dermatitis. Creams containing alginates form versatile films with enhanced skin adhesion, making them suitable for a variety of cosmetic applications [211].

Alginate exhibits various properties relevant to cosmetics and wellness products, particularly anti-allergic properties [212,213]. This action is observed in hydrogel formulations with alginate [214] and may contribute to preventing obesity [215–217].

4.3. Carrageenan

Certain species of red seaweed belonging to various families of the order Gigartinales, known as carrageenophytes, produce a pure polysaccharide known as “carrageenin”. However, carrageenin is unstable and difficult to extract; thus, it binds to one or more cations to form different carrageenan salts (carrageenans), which constitute approximately 30% to 75% of the seaweed’s dry weight. These linear sulfated polygalactans are composed of alternating residues of galactose linked by (1–3) and (1–4) bonds [218]. From a commercial perspective and according to several regulatory authorities (e.g., FDA, EFSA), carrageenan has been classified as safe based on minimal or no adverse physiological impacts observed in toxicological evaluations. The most important types of carrageenans are kappa (κ), iota (ι), and lambda (λ). Gelling properties are characteristic of iota and kappa carrageenan, while lambda carrageenan exhibits thickening properties [219–221]. Carrageenan can be extracted from various red seaweeds, such as *Betaphycus gelatinus*, *Chondrus crispus*, *Eucheuma denticulatum*, *Sarcopeltis skottsbergii* (formerly *Gigartina skottsbergii*), *Kappaphycus alvarezii*, *Hypnea musciformis*, *Mastocarpus stellatus*, *Mazzaella laminarioides*, and *Sarcothalia crispata*, which are valuable for several industries. More than 20% of carrageenan production is used in pharmacy and cosmetics. Many everyday cosmetic products contain carrageenan in their formulations, including toothpastes, hair wash products, lotions, medicines, sunscreens, shaving creams, deodorant sticks, sprays, and foams [222–224]. Research has demonstrated the diverse bioactive properties of carrageenan. Its ability to form hydrogels allows for applications in various areas due to its antiviral, antibacterial, and management effects on pathophysiological processes such as hyperlipidemia. These properties make carrageenan compelling for use in various applications, given its reported high safety, effectiveness, biocompatibility, biodegradability, and non-toxicity. However, further studies are necessary to fully assess the potential effectiveness of carrageenan [225,226].

4.4. Porphyran

Porphyran, a well-researched group of sulfated polysaccharides extracted aqueously, is derived from red seaweeds such as *Porphyra*/*Pyropia* and *Bangia* species. Structurally, porphyran is a linear polysaccharide composed of glycosidic linkages between repeated and alternated units of substituted -D-galactopyranose at carbon 3 and -L-galactopyranose units substituted at carbon 4, arranged in a disaccharide pattern represented as [!3)--D-galactopyranose-(1!4)--L-galactopyranose-(1!] n. Research indicates porphyran's potential applications in skin whitening, anti-inflammatory, pain relief, and antiulcer activities, making it appealing for cosmeceutical use [227–229].

4.5. Laminaran

Laminaran, also known as laminarin or leucosin, is a glucan that can exist in either soluble or insoluble forms. The soluble form dissolves completely in cold water, while the insoluble form is soluble only in hot water [230]. Structurally, laminaran consists of _-(1,3)-linked D-glucose with intra-chain branching of _-(1,6). This polysaccharide is predominantly found in seaweeds belonging to the class Phaeophyceae (brown algae), including *Laminaria* and *Saccharina*, and in smaller amounts in *Ascophyllum*, *Fucus*, *Sargassum*, and *Undaria*. Laminarans have been studied for their anti-tumoral, anti-inflammatory, anticoagulant, antiviral, and antioxidant properties. In cosmetics, laminarins are commonly used in products targeting cellulite reduction [231–234].

Laminarin sulfate, known for its wound healing properties, has led to the development of novel hydrogel systems [235–238]. Additionally, promising outcomes have been demonstrated in numerous biomedical applications, including tissue engineering, cancer therapies, and antioxidant and anti-inflammatory properties [239]. Degradation by irradiation can enhance radical scavenging capacity and inhibitory activity against melanin synthesis in melanoma cells [240,241].

4.6. Fucoidan

Fucoidan, a hydrocolloid mainly composed of α-L-fucopyranose residues, unveils a heterogeneous and dynamic structure and composition. Besides α-L-fucose and sulfates, this molecule can also contain other monosaccharides, such as galactose, xylose, mannose, rhamnose, glucose, and/or uronic acids, or even acetylated groups. Moreover, there can also be differences among the molecular weight, branching, and substitutions according to the targeted species, as well as the selected extraction and purification methods [242]. These sulfated polysaccharides are interesting due to the wide range of bioactivities they present, such as the prevention of obesity, diabetes, and tumor development, as well as their anti-coagulant, anti-thrombotic, anti-inflammatory, UV blocker, tyrosinase inhibitor, antibacterial, antioxidative, and antihyperlipidemic activities [243–246]. Fucoidans' anticoagulant bioactivity is highlighted by several authors, who claim that this polysaccharide extracted from the seaweeds *Eklonia cava* and *Fucus vesiculosus* has the ability to inhibit thrombin, which is mediated by anti-thrombin III plasma, mimicking the heparin activity [247–249]. In general, studies on the anticoagulant/anti-thrombin activity of fucoidans reported that they are directly dependent on the molecular weight, concentration, and/or placement of polysaccharide sulfate groups. Furthermore, binding and branching forms and their monomeric composition can also play an essential role in modulating the biological properties of these sulfated polysaccharides [250,251]. In fact, Moon et al. [252] found that, when the skin is exposed to UVB (ultraviolet B) radiation, fucoidan can promote the synthesis of procollagen type I and the inhibition of the expression of the metalloproteinase matrix. So, it is theorized that this polysaccharide can be employed as a therapeutic agent in order to prevent skin photoaging. In addition, studies have shown that fucoidans application in human leukocytes can decrease elastase activity, protecting the elastic fibers of the skin. Fucoidans also act as tyrosinase inhibitors and can, as well, minimize skin pigmentation [252,253]. Fucoidan can also protect the hair and skin by eliminating free radicals, reducing inflammation, wrinkles, allergies, and sensitive skin reactions. This polysaccharide can also promote skin elasticity, firmness, and brightness, as well as hair safety, growth, rigidity, cleanliness, and gloss [222]. The effects of fucoidan rely on a variety of cellular and molecular mechanisms, such as radical scavenging, down-regulation of COX-1/2, MAPK p38, inhibition of hyaluronidase, DPP-IV, and extension of APTT and TT. Literature shows that molecular weight, sulfate and fucose content, and polyphenols may have a role in these activities [254–256].

Fucoidans, heteropolysaccharides containing fucose and other monosaccharides like xylose, galactose, mannose, and glucuronic acid, along with sulfate, uronic acids, and acetyl groups, offer potential as cosmetic ingredients [257–259]. They are non-toxic, biodegradable, and biocompatible [260,261], with diverse biological properties [170,262–267], including antioxidant and antiradical effects [268–271]. These properties vary depending on molecular weight and sulfate content [272,273]. Fucoidans have demonstrated benefits in preventing and treating skin photoaging, inhibiting UVB-induced collagenase and gelatinase activities, and ex vivo inhibition of elastase activity in human skin [122,274–276]. They also inhibit wrinkle-related enzymes, enhance collagen synthesis in human dermal fibroblasts, and possess anti-inflammatory action against extracellular matrix degradation by matrix metalloproteinases [277–279].

4.7. Ulvan

Ulvan is a hydrocolloid extracted from green seaweeds, constituting approximately 8% to 29% of the algae's dry weight. Its composition includes rhamnose, xylose, glucose, mannose, galactose, and uronic acids, forming two main repetitive disaccharides: ulvanobiuronic acids type A [(!4)-α-D-GlcA-(1!4)-α-L-Rha 3S-(1!)] and type B [(!4)-α-L-IdoA(1!4)-α-L-Rha 3S-(1!)]. However, variations in polysaccharide structure may occur due to taxonomic and/or eco-physiological differences [175,280]. Ulvan exhibits gelling properties in the presence of divalent cations like Ca^{2+}, Cu^{2+}, and Zn^{2+}, within a pH range of 7.5 to 8.0, and it can withstand temperatures up to 180 °C. These rheological and bio-functional properties make ulvans appealing as raw materials for cosmeceuticals [281]. The gel formation mechanism of ulvans is complex, involving the creation of spherical structures in the presence of boric acid and calcium ions. Ulvans possess moisturizing, protective, antitumor, and antioxidative properties [282–286]. Ulvan finds applications as clouding and flavoring agents in beverages and as stabilizers in cosmetics, owing to its desirable characteristics [287,288]. Moreover, the antioxidant activity of ulvan is of interest to the cosmetic industry due to its demonstrated ability to protect against hydrogen peroxide-induced oxidative stress in vitro. Additionally, the presence of glucuronic acid, known for its moisturizing properties, and rhamnosyl residues, studied for their roles in cell proliferation and collagen synthesis, further enhance ulvan's appeal as a raw material for the cosmetic industry [289,290].

Ulvans, complex and variable sulfated polysaccharides from ulvales, are primarily composed of rhamnose, xylose, glucose, glucuronic acid, iduronic acid, and sulfate [291,292]. They exhibit a range of activities, including gelling, anti-aging, anti-hyperlipidemic, and antiherpetic properties [293–296]. Additionally, seaweed and seaweed-derived compounds' skin benefits/activities are noted in Table 2 below.

Table 2. Therapeutic potential of seaweed compounds for skin health.

Seaweed/s	Compound	Properties/Activities	References
Sargassum tenerrimum	Fucoidan	Antioxidant: Decrease in DPPH radical and superoxide radical, high total antioxidant and FRAP ability	[297–300]
Costaria costata	Fucoidan	Skin anti-aging: Decrease in UVB-induced mRNA and protein expression of MMP-1, increase in type 1 pro-collagen, and decrease in activation of ERK and JNK	[301,302]
Laminaria cichorioides	Fucoidan	Anti-atopic dermatitis: Reduction in DNCB-induced atopic dermatitis symptoms, including clinical severity scores, scratching counts, and serum histamine levels	[303]
Costaria costata	Fucoidan	Skin anti-aging: Decrease in expression of MMP-1 and increase in type 1 pro-collagen	[276,304]
Sargassum tenerrimum	Fucoidan	Anti-melanogenesis: Activation of the ERK pathway leading to a decrease in melanin content	[305]
Mekab	Fucoidan	Skin anti-aging: Decrease in UVB-induced edema, thickness of prickle cell layer, and MMP-1 activity and expression	[306]
Ascophyllum nodosum	Fucoidan (16 kDa)	Skin elasticity: Decrease in elastic fiber degradation and leukocyte elastase activity	[307]
Ascophyllum nodosum	Fucoidan (16 kDa)	Inflammatory response: Reduction in IL-1β-induced MMP-9 and MMP-3 expression/secretion, increase in TIMP-1	[308]
Laminaria cichorioides	Fucoidan	Atopic dermatitis: Reduction in AD-associated chemokines, including TARC, MDC, and RANTES	[309]
Laminaria cichorioides	Fucoidan	Atopic dermatitis: Decrease in IgE production in PBMC from patients with AD and immunoglobulin germline transcripts of B cells	[310]
Saccharina longicruris	Laminaran	Skin tissue engineering: Increase in deposition of matrix	[311]
Saccharina japonica	Fucoidan	Moisturizing: Higher moisture absorption and retention ability compared to HA	[312]
Laminaria cichorioides	Fucoidan (water soluble)	Skin cancer prevention: Decrease in EGF or TPA-induced neoplastic cell transformation and binding of EGF and EGFR	[313]
Ulva pertusa	Ulvans	Antioxidant: Reduction in superoxide and hydroxyl radicals, increase in reducing power and metal chelating ability	[314,315]
Saccharina longicruris	Laminaran	Skin anti-aging: Decrease in UVA+UVB-induced skin dermal thickness, increase in Hyp content, decrease in MMP-1 expression, and increase in TIMP-1	[316]
Ulva sp.	Crude ulvans (57 kDa)	Skin anti-aging: Increase in hyaluronan production and decrease in collagen release	[317]
Eucheuma spinosum (*Eucheuma denticulatum*) *Eucheuma*	Carrageenan	Antioxidant, Photoprotective: Decrease in UVB-induced cell death, intracellular ROS, and DPPH radical	[318]

cottonii (*Kappaphycus alvarezii*)			
Porphyra sp.	Porphyran	Antioxidant: Ferrous ion chelating, increase in reducing power, decrease in DPPH radical and superoxide	[319]
Porphyridium sp.	Carrageenan	Anti-melanogenesis: Decrease in level of melanosome	[320]
Porphyra haitanensis	Porphyran	Antioxidant: Increase in antioxidant enzyme activity, decrease in lipid peroxidation, increase in total antioxidant capacity	[321,322]
Porphyra haitanensis	Porphyran with different MW	Antioxidant: Decrease in DPPH radicals, increase in reducing power	[323]
Porphyra yezoensis	Porphyran	Ꮖ Anti-inflammation: Decrease in LPS-induced inflammatory markers including NO, iNOS, NF-κB activation, and TNF-α production	[324,325]
Porphyra haitanensis	LMW Porphyran SD, AD, PD, BD	Antioxidant: Decrease in DPPH radicals, hydroxyl radicals, and superoxide	[326]

4.8. Remarks

Seaweeds possess a significant carbohydrate fraction forming their cell walls, with specific polysaccharides characteristic of each type of algae: brown algae contain alginate, laminaran, and fucoidan; green algae feature ulvan; and red algae are rich in agar and carrageenan. Polysaccharides are garnering increasing attention due to their bio-functional and physicochemical properties [327]. Sulfated polysaccharides, in particular, are highly regarded for their health benefits and diverse biological activities [170,328–334]. A critical aspect of these polysaccharides is the close relationship between their activity and composition, particularly their molecular weight. Depolymerization is often proposed to enhance activity [170], although other structural modifications are also feasible. Simple hydrophobization reactions, such as esterification, acylation, alkylation, amidation, or cross-linking reactions on native hydroxyl, amine, or carboxylic acid groups, can also enhance bioactivity [335,336].

Sulfated polysaccharides from green algae, such as rhamnans, arabinogalactans, galactans, and mannans, have variable compositions and structures, with properties highly influenced by molecular weight, particularly in terms of antiradical and chelating properties [337–340].

Agarooligosaccharides (AOS) and carrageenan-oligosaccharides (COS) demonstrate enhanced biological properties compared to native polysaccharides, particularly in terms of prebiotic, antitumoral, and antioxidant actions, attributed to their chemical structure, molecular weight, degree of polymerization, and glycosidic linkage flexibility [341]. The chemical structures of different red-algae-derived oligosaccharides are shown in Figure 2 below.

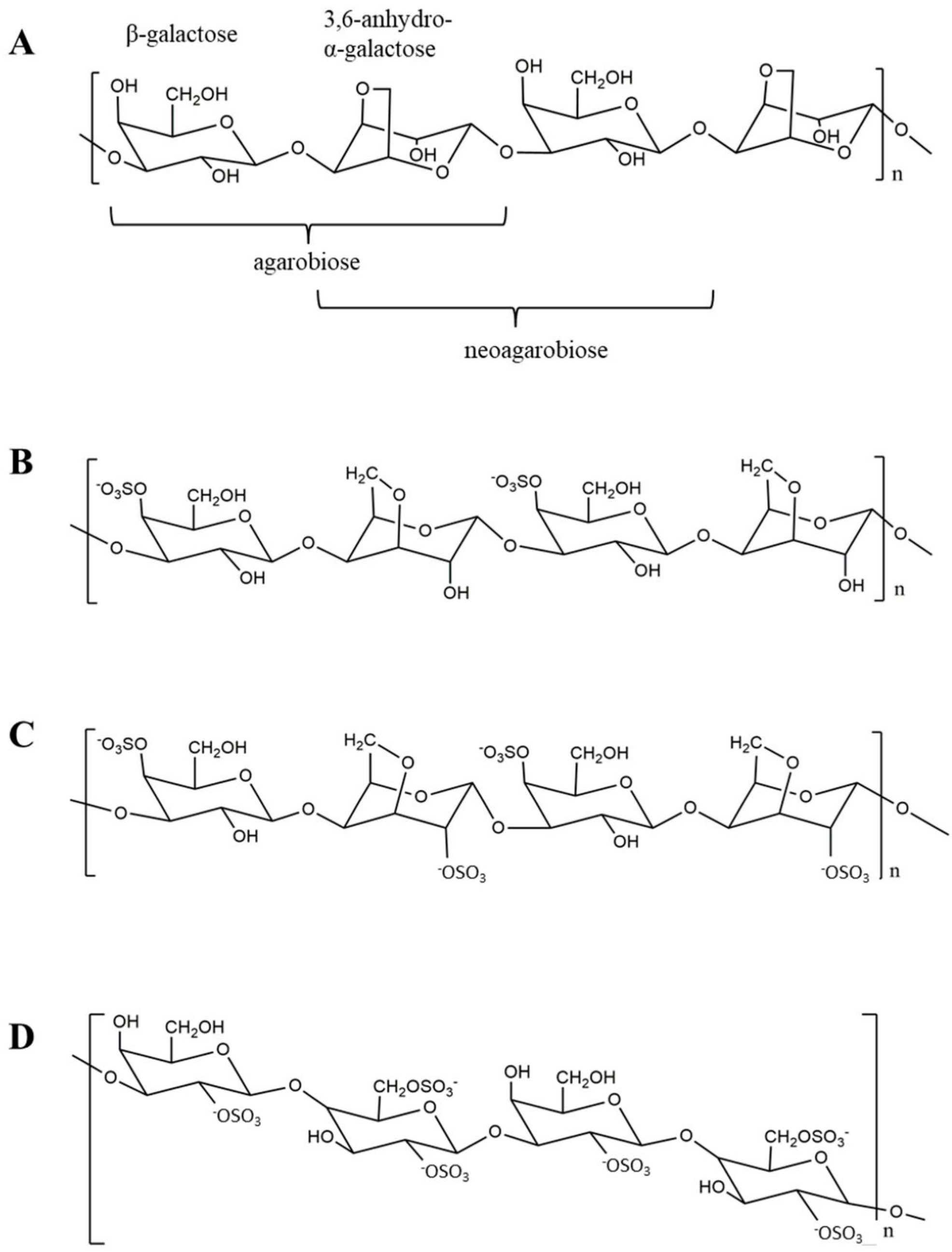


Figure 2. Diagrammatic representation of oligosaccharides derived from red seaweed. (**A**) Agaro–oligosaccharides and neoagaro–oligosaccharides; (**B**) κ–carrageenan oligosaccharides; (**C**) ι–carrageenan oligosaccharides; and (**D**) λ–carrageenan oligosaccharides. Source: Cheong et al. [342].

5. Seaweed-Derived Proteins, Peptides, and Amino Acids for Skin Benefits

Proteins, comprising one or more amino acid chains, are vital biological macromolecules found in all living organisms, playing essential roles in numerous cellular processes, including DNA replication, signal transduction, and molecular transport. Many proteins serve as enzymes that catalyze biochemical reactions crucial for various metabolic pathways [343]. Seaweed contains proteins in various forms, either as single or conjugate entities, often accompanied by protein derivatives and free amino acids like enzymes or peptides [344]. The bioactivity of proteins depends on their chemical structure and cellular localization, offering diverse cosmetic applications such as anti-tumor and anti-inflammatory properties, antioxidant effects, anti-aging benefits, and skin protection. Hence, seaweed proteins are utilized as moisturizers for hair and body and effectively serve as cosmeceuticals [345]. Amino acids, abundant in seaweed, play roles as hydrating agents in cosmetic products, many of them being integral components of the natural moisturizing factor (NMF) in human skin [346]. Seaweed is a rich source of both non-essential amino acids like alanine, serine, and proline, as well as essential amino acids such as histidine, tyrosine, and tryptophan [347]. For instance, *Ulva australis* exhibits antioxidant and antihypertensive effects due to its content of histidine and taurine [348]. Additionally, red seaweeds like *Palmaria palmata* (Dulse) and brown seaweeds like *Himanthalia elongata* (Sea Spaghetti) are noted for their abundance in serine, alanine, and glutamic acid [349]. Mycosporine-like amino acids (MAAs) are secondary metabolites found in seaweed, crucial for absorbing sunlight and protecting marine organisms from UV radiation [350]. MAAs are particularly abundant in red seaweeds such as *Chondrus crispus*, *Palmaria palmata*, *Gelidium* sp., *Porphyra/Pyropia/Neopyropia* sp., *Gracilaria cornea*, *Asparagopsis armata*, *Solieria chordalis*, *Grateloupia lanceola*, and *Curdiea racovitzae*. These compounds serve as effective UV protectors and stimulate cell proliferation in cosmetics and personal care products [351]. Different types of bioactive peptides, phycobiliproteins, and MAAs are shown in Figure 3 below.

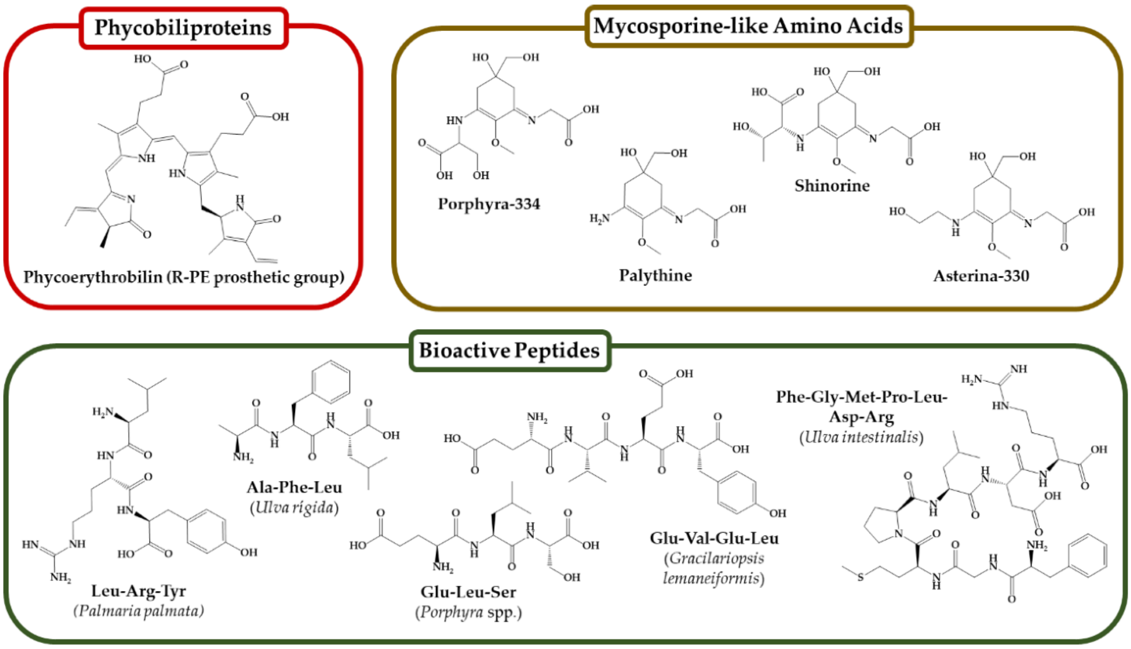


Figure 3. Structural representation of bioactive compounds from seaweed: chromophore group of R-phycoerythrin, mycosporine-like amino acids, and peptides. Source: Echave et al. [352].

Seaweeds serve as a rich protein source, with cultivation offering higher protein yields per unit area compared to terrestrial crops (2.5–7.5 tons/ha/year), although successful extraction is influenced by the presence of polysaccharides like alginates in brown seaweed or carrageenans in red seaweed [353]. Seasonal variations and habitat conditions affect the protein, peptide, and amino acid contents in seaweed; red algae generally exhibit higher contents (up to 47%) than green (between 9–26%), while brown algae have a lower concentration (3–15%) [354–357]. Proteins from all three macroalgae groups contain essential and non-essential amino acids, with bioactive peptides demonstrating numerous health benefits and high antioxidant properties, particularly those with low molecular weights, which are considered safer than synthetic molecules with reduced side effects [358–365]. Also, different dermatological benefits are tabulated in Table 3.

Table 3. Bioactivity of seaweed extracts and seaweed-derived peptide compounds in dermatological applications.

Extract/Compound	Activity	Seaweed	References
Eleven mycosporine-like amino acids	UV-protective effect, antioxidant	*Agarophyton chilense*, *Pyropia plicata*, *Champia novaezelandiae*	[366]
Mycosporine-like amino acids extract	Anti-aging	*Phorphyra umbilicalis*	[367]
Mycosporine-like amino acids extract	Antioxidant, UV-protective effect, anti-aging	*Curdieara covitzae*, *Iridaea cordata*	[368]
Mycosporine-like amino acids extract	Antioxidant; UV-protective effect	*Gracilaria vermiculophylla*	[369]
Mycosporine-like amino acids extract	Antioxidant, antiproliferative	*Chondrus crispus*, *Mastocarpus stellatus*, *Palmaria palmata*	[370]
Mycosporine-like amino acids extract	Antioxidant	*Rhodymenia pseudopalmata*	[371]
Aqueous extract from freshwater macroalga	Skin moisturizing effect	*Rhizoclonium hieroglyphicum*	[372]
Peptide PPY1	Anti-inflammatory	*Pyropia yezoensis*	[373]
Peptides PYP1-5 and porphyra 334	Increase in the production of elastin and collagen	*Porphyra yezoensis f. coreana* Ueda	[374]
Methanol extract rich in proteins, vitamins, minerals, porphyra-334 and shinorine	Hydration, skin protective, anti-wrinkle, anti-roughness	*Phorphyra umbilicalis*	[375]
Phycobiliproteins (R-phycoerythrin allophycocyanin and phycocyanin)	Antioxidant	*Gracilaria gracilis*	[376]
Hydrolyzed extract	Antitumor	*Porphyra haitanensis*	[377]
Algae extract	Decrease in progerin production, anti-elastase, and anti-collagenase	*Alaria esculenta*	[378]

Peptides Bioactivities

Bioactive peptides typically comprise 3–20 amino acid residues, with their activities, including antioxidant and antimicrobial effects, influenced by both amino acid composition and sequence [379–382]. Examples of such peptides include carnosine, glutathione, and taurine, which exhibit antioxidant and chelating properties [383]. Taurine, although lacking a carboxyl group, possesses health-promoting properties and accumulates in various red algae species, such as *Ahnfeltia plicata*, *Euthora cristata*, and *Ceramium virgatum* [384]. PPY1, a peptide derived from *Pyropia yezoensis* through enzymatic hydrolysis, demonstrates anti-inflammatory effects by suppressing inflammatory cytokines [385]. Peptides like PYP1-5 and Porphyra 334, extracted from *Porphyra yezoensis* f. *coreana*, enhance elastin and collagen production while inhibiting the expression of matrix metalloproteinases (MMP) [386]. Ultrasound-assisted enzymatic hydrolysis has been proposed for extracting iodinated amino acids from red seaweeds like *Palmaria palmata* and *Porphyra umbilicalis* [387]. Moreover, seaweed-derived enzymes and peptide-related compounds with their bioactivity are represented in Table 4.

Table 4. Biological activities of enzymatically derived compounds from seaweed species.

Species	Hydrolysis	Bioactivity	Results	Ref.
Ulva lactuca	Papain	In vitro, antihypertensive	ACE inhibition (93%) in the >1 kDa hydrolysate fraction	[388]
Laminaria japonica	Alcalase, papain, trypsin, and pepsin	In vitro, antihypertensive	ACE inhibition. The hydrolysate of all combined proteases achieved an IC50 = 0.6 mg/mL	[389]
Enteromorpha clathrata	Alcalase	In vitro, antihypertensive	ACE inhibition. IC50 = 0.014 mg/mL	[390]
Saccharina longicruris	Trypsin	In vitro, antimicrobial	A mix of all peptides (2.50 mg/mL) inhibited 40% of Staphylococcus aureus growth	[391]
Porphyra dioica	Alcalase and flavoenzyme	In vitro, antioxidant	Most antioxidants on the ORAC assay: IC50 (AFIT) = 0.4 μg/mL, IC50 (MKTPITE) = 0.007 mg/mL	[392]
Sargassum maclurei	Pepsin	In vivo and in vitro, antihypertensive	Systolic blood pressure reduction from 170 to 150 mm Hg at 100 mg/kg bw; 25% endothelin-1 inhibition at 1.5 mg/mL	[393]
Caulerpa lentillifera	Thermolysin	In vitro, antihypertensive	ACE inhibition. IC50 (FDGIP) = 0.03 mg/mL, IC50 (AIDPVRA) = 0.04 mg/mL	[394]
Gracilariopsis lemaneiformis	α-Chymotrypsin	In vitro, antioxidant	DPPH radical scavenging, EC50 = 1.51 mg/mL	[395]
Porphyra dioica	Prolyve	In vitro, antioxidant	ORAC (IC50 = 2.7 mmol TE/g), DPPH (IC50 = 0.2 mmol TE/g), FRAP (IC50 = 0.4 mmol TE/g)	[396]
Porphyra yezoensis	Chemical synthesis	In vitro, antitumor	Doses ≥ 125 ng/mL induced autophagy and apoptosis in MCF-7 cells via the mTOR pathway	[397]
Pyropia columbina	Trypsin	In vitro, antioxidant and anti-inflammatory	DPPH (IC50 = 2.8 mg/mL), ABTS (IC50 = 2.4 mg/mL); upregulation of IL10 at 0.1 mg/mL	[398]
Palmaria palmata	Chymotrypsin	In vitro, antioxidant and antihypertensive	A < 10 kDa fraction was the most bioactive at ≥0.75 mg/mL	[399]
Pyropia columbina	Fungal protease	In vitro, anti-inflammatory	Upregulation of IL-10 in murine spenocytes, macrophages, and lymphocytes at ≥0.01 mg/mL	[400]
Neopyropia yezoensis	Chemical synthesis	In vitro, anti-inflammatory	Doses ≥ 250 ng/mL inhibited the expression of inflammatory cytokines in murine macrophages	[401]
Bangia fusco-purpurea	Pepsin	In vitro, antihypertensive	ACE inhibition. IC50(ALLAGDPSVLEDR) = 57.2 mg/mL, IC50(VVGGTGPVDEWGIAGAR) = 66.2 μg/mL	[402]

Mycosporine-like amino acids (MAAs) are secondary metabolites synthesized by marine organisms for protection against solar radiation [403–405]. Comprising cyclohexenone or cyclohexenimine chromophores with various amino acids, mainly glycine or iminoalcohol groups, as substituents, MAAs exhibit antioxidant and photoprotective properties [406–412]. Rhodophyceae species contain abundant MAAs such as shinorine, porphyra-334, palythine, asterina-330, mycosporine-glycine, palythinol, and palythene, with their contents varying based on geographic, seasonal, and bathymetric conditions, peaking during summer, and decreasing with water depth [413,414].

A multifunctional cosmetic liposome formulation incorporating UV filters, vitamins (A, C, and E), *Ginkgo biloba* extract (rich in quercetin), and *Porphyra umbilicalis* extract (abundant in proteins, vitamins, minerals, and MAAs such as porphyra-334 and shinorine) effectively combats signs of aging by improving hydration and reducing wrinkles and skin roughness [375,415]. Extracts like ASPAR'AGE™ from *Asparagopsis armata* and Aosaine® from *Ulva lactuca*, rich in amino acids, enhance skin elasticity, reduce wrinkles, and stimulate collagen production [416]. Similarly, extracts from *Gelidium corneum*, containing minerals, trace elements, and amino acids, improve skin softness and elasticity. MAAs offer diverse properties, serving as natural sunscreens, antioxidants, anti-inflammatories, and anti-aging agents, and stimulating skin renewal and cell proliferation, making them promising options for pharmaceutical and cosmetic applications [417].

Given the toxicity of synthetic dyes and the demand for natural colors in various industries, there is growing interest in phycobiliproteins like C-phycocyanin (used in food) and R-phycoerythrin (used in cosmetics). Phycobiliproteins are water-soluble compounds comprising proteins covalently bound to phycobilins, acting as reddish colorants [277,418–422]. B-phycoerythrin, resistant to pH changes, exhibits antioxidant properties and serves as a pink or purple dye in cosmetics [423,424]. Extracted from *Gracilaria gracilis*, phycobiliproteins show high antioxidant and radical-scavenging activities, particularly during winter harvests [425]. Extraction methods using aqueous solutions of ionic liquids, such as cholinium chloride, can yield up to 46.5% of R-phycoerythrin from fresh algal biomass [426]. Studies on *Furcellaria lumbricalis* and *Coccotylus truncatus* demonstrate an exponential correlation between R-phycoerythrin and allophycocyanin concentrations and collection depth [427]. Additionally, phycoerythrin and phycocyanin contents in dried *Porphyra* sp. extracts are slightly higher and lower, respectively, compared to *Spirulina* sp. [428].

Proteins, as macromolecules composed of amino acids, play a crucial role in skincare, acting as natural moisturizing factors that help prevent water loss from the skin [429]. Marine macroalgae are rich sources of various amino acids, including glycine, alanine, valine, leucine, proline, arginine, serine, histidine, tyrosine, and mycosporine amino acids (MAAs), offering numerous benefits for skin health and cosmetics [430]. Essential amino acids like histidine, tyrosine, and tryptophan, along with non-essential amino acids such as alanine, serine, and proline, are abundant in macroalgae, contributing to their antioxidant properties [431]. For instance, *Ulva australis*-derived amino acids like histidine and taurine exhibit antioxidant activity [432], while red macroalgae like *Palmaria palmata* and brown algae like *Himanthalia elongata* are rich in glutamic acid, alanine, and serine [433].

MAAs found in seaweeds play essential roles in protecting against UV radiation damage, scavenging radicals, and aiding DNA repair systems, making them valuable for UV protection and antioxidant activity in cosmetics [434]. Peptides derived from *Pyropia yezoensis* have been shown to increase elastin and collagen production and reduce the expression of matrix metalloprotein (MMP), contributing to anti-aging effects [374,435]. MAAs from *Gracilaria* genus species exhibit photoprotection activity [436,437], while Porphyra-334 obtained from *Porphyra umbilicalis* acts as an effective UV filter, reducing intracellular radical oxygen species and MMP expression [438,439]. MAAs also demonstrate antioxidant, anti-aging, and anti-inflammatory activities, scavenging reactive oxygen species, increasing UV-suppressed gene expression, and reducing inflammatory markers like COX-2 and involucrin expression [440]. Various seaweeds, including *Dixoniella grisea*, *Ecklonia cava*, and *Undaria pinnatifida*, have been reported for their antioxidant activity [441–444]. Peptides derived from *Pyropia yezoensis* stimulate collagen synthesis and elastin synthesis and suppress MMP-1 protein expression, contributing to anti-aging effects [445]. Additionally, proteins and amino acids from marine sources offer numerous skin benefits, including anti-inflammatory, antioxidant, antitumor, anti-aging, protective, and moisturizing effects in cosmetics [440,446,447]. *Ulva australis* is noted for its richness in essential amino acids like histidine and taurine [447], while red algae like *Palmaria palmata* and *Himanthalia elongata* are abundant in serine, alanine, and glutamic acid [448–450]. MAAs, such as those found in various red macroalgae, serve as UV protectors and cell proliferation activators in cosmetics [440,451,452]. MAAs like Porphyra-334 and Shinorine from *Pyropia elongata* (formerly *Porphyra rosengurttii*) demonstrate photostability and photoprotection against UV radiation, preventing sunburn cell formation and protecting against UV-induced skin thickening [453,454]. These compounds hold promise for preventing skin damage and promoting skin health in cosmetic applications.

6. Future Roads toward Seaweed-Based Cosmetics

Seaweeds, abundant and diverse marine organisms, have emerged as a promising reservoir of bioactive compounds with significant implications for skincare and cosmetic formulations. Within this intricate matrix of marine-derived ingredients, polysaccharides, proteins, peptides, and amino acids play pivotal roles, offering a diverse array of benefits for enhancing skin health and beauty. Polysaccharides extracted from seaweeds encompass a rich diversity of compounds, each possessing unique physicochemical characteristics that render them indispensable assets in the realm of cosmetic science. These polysaccharides, including agar, alginic acid, carrageenan, porphyran, laminaran, fucoidan, and ulvan, offer a broad spectrum of functionalities that extend far beyond their roles as mere thickeners, stabilizers, and emulsifiers. Delving deeper into their multifaceted nature reveals a treasure trove of bioactive properties, serving as the cornerstone for their integration into cosmetic formulations. Beyond their conventional uses, they demonstrate remarkable antioxidant capabilities, effectively combating oxidative stress and free radical damage, which are primary contributors to premature skin aging. Additionally, their anti-inflammatory effects provide soothing relief for irritated or inflamed skin, promoting a calmer and more balanced complexion. Moreover, these polysaccharides exhibit exceptional moisturizing properties, imparting hydration to the skin by attracting and retaining moisture, thus enhancing skin suppleness and resilience. Their innate ability to form protective barriers on the skin surface shields against environmental pollutants and UV radiation, contributing to overall skin health and vitality.

The versatility of these polysaccharides transcends traditional cosmetic boundaries, permeating a wide spectrum of skincare products. From opulent creams and serums that lavish the skin with indulgent nourishment to everyday essentials like cleansers and sunscreens that provide essential protection, their inclusion elevates formulations to new heights. Moreover, their sensorial qualities enhance the user experience, imbuing products with luxurious textures and pleasurable application rituals. As the cosmetic industry continues to innovate, these seaweed-derived polysaccharides stand poised as indispensable ingredients, offering a harmonious fusion of science and nature. Their multifunctional nature and diverse benefits underscore their relevance in meeting the evolving demands of consumers for effective, safe, and sustainable skincare solutions. In essence, the polysaccharides extracted from seaweeds represent a cornerstone of modern cosmetic science, embodying a symphony of functional and sensorial attributes that enrich formulations and elevate skincare experiences. Their boundless potential continues to inspire exploration and innovation, promising a bright future for seaweed-based cosmetics in the pursuit of radiant and healthy skin.

Proteins, peptides, and amino acids derived from seaweeds serve as fundamental pillars within marine-inspired skincare formulations, constituting a rich repertoire of bioactive compounds with multifaceted benefits for skin health and rejuvenation. Their multifunctional properties extend across various aspects of skincare, ranging from hydration and antioxidant protection to anti-inflammatory action, making them indispensable ingredients in the pursuit of radiant and youthful-looking skin. At the forefront of this marine skincare revolution are mycosporine-like amino acids (MAAs), abundantly present in seaweeds. These remarkable compounds serve as potent photoprotectors, effectively shielding the skin from the harmful effects of UV radiation. By absorbing and dissipating UV rays, MAAs mitigate the risk of sunburn, premature aging, and DNA damage, thereby bolstering the skin's resilience against environmental stressors. Their innate ability to combat solar-induced skin damage underscores their significance in skincare formulations, offering a natural and sustainable approach to sun protection.

Additionally, proteins, peptides, and amino acids from seaweeds function as natural moisturizing factors, replenishing the skin's hydration levels and maintaining its moisture barrier integrity. By attracting and retaining water molecules, these compounds help to prevent dehydration, dryness, and roughness, promoting a plump, smooth, and supple complexion. Moreover, their antioxidant properties neutralize free radicals, reducing oxidative stress and minimizing the appearance of fine lines, wrinkles, and other signs of aging. This dual action of hydration and antioxidant protection ensures optimal skin health and vitality. Furthermore, phycobiliproteins, serving as both natural colorants and antioxidants, enhance the allure of seaweed-based cosmetic formulations. Beyond their aesthetic appeal, these vibrant pigments offer additional skincare benefits, including antioxidant protection and brightening effects. By neutralizing harmful free radicals and promoting skin radiance, phycobiliproteins contribute to a luminous and healthy complexion, further enhancing the efficacy of marine-inspired skincare products.

In summary, proteins, peptides, amino acids, MAAs, and phycobiliproteins sourced from seaweeds represent a goldmine of bioactive compounds with unparalleled potential in skincare formulations. Their multifunctional properties, encompassing hydration, antioxidant protection, photoprotection, and aesthetic enhancement, make them invaluable assets in the quest for youthful and radiant skin. As the beauty industry continues to embrace natural and sustainable ingredients, seaweed-derived compounds stand at the forefront of innovation, offering safe, effective, and eco-friendly solutions for skincare enthusiasts worldwide. The integration of seaweed-derived ingredients into cosmetic formulations not only satisfies the growing demand for natural, sustainable skincare solutions but also embodies a comprehensive approach to skincare that addresses a wide array of concerns, spanning from hydration and elasticity to shielding against external aggressors. This holistic perspective underscores the multifaceted benefits of seaweed extracts, which offer not only cosmetic enhancement but also therapeutic properties that promote skin health and resilience. Furthermore, the renewable nature of seaweed resources highlights their potential to drive innovation within the cosmetic industry while simultaneously minimizing environmental impact. As consumer preferences increasingly shift towards eco-conscious beauty products, the utilization of seaweed-derived compounds aligns with this trend, offering a sustainable alternative to traditional skincare ingredients sourced from non-renewable or environmentally taxing sources.

Future Prospects Towards Seaweed-Based Cosmetics for Safe Applications

Cosmetic raw ingredient supply is becoming increasingly important in terms of sustainability and environmental responsibility. Future advancements may include the production of targeted seaweed species in controlled cultivation in specific areas, which reduces environmental impact, enhances compound stability and purity rate, and ensures a reliable supply chain. Seaweed extracts might be used in formulations tailored to certain skin types and issues, resulting in a more focused and successful approach. Biotechnological procedures, including genetic manipulation and bioengineering, might be used to increase the production of beneficial substances in seaweed. This might lead to the creation of seaweed types with improved characteristics for cosmetic use.

Continued research into novel green extraction technologies will promote more effective extraction of specific compounds from cultivated seaweed. This increases the production, purity, and safety of targeted components, ensure their efficacy in cosmetic compositions and reduce the problems of contaminants or impurities. Formulators need to look for the chemical and biochemical interactions between seaweed extracts, compounds, and other natural substances renowned for their skincare advantages. Combining seaweed with plant extracts, vitamins, and antioxidants can result in potent, multifunctional cosmetic products.

Beyond topical uses, the cosmetic industry and RD teams can start to study the use of seaweed extracts in functional meals and nutricosmetics. Seaweed-based food products can help improve skin health and appearance by changing the human metabolism. However, for this to happen, there is a need to create and develop rigorous clinical trials to establish their efficacy and safety. In conclusion, scientific research will be vital in determining the advantages of seaweed for skin health in the future. Also, this green future trend needs to include more attempts to educate the public about the benefits of seaweed-based cosmetics and their problems. And regulatory organizations need to develop more specific criteria and requirements for the incorporation of seaweed extracts in skincare products because, today, there are few requirements to assure product safety and quality. Ultimately, the future of seaweed-based cosmetics is tending to be defined by a complex mix of scientific developments, industrial research, pharmaceutical safety approaches, environmental concerns, customer tastes, and a dedication to safe, responsible, and ethical sourcing.

7. Conclusions

This review demonstrated the potential of the exploitation of seaweed polysaccharides and proteins into natural cosmetics. Furthermore, continued exploration and research into the mechanisms of action, formulation optimization, and sustainable sourcing of seaweed-derived compounds are crucial for unlocking their full potential in skincare. By delving deeper into the bioactive properties of seaweeds and refining extraction techniques, scientists and skincare experts can further enhance the efficacy and versatility of these natural ingredients, paving the way for groundbreaking advancements in cosmetic science. Moreover, the synergistic combination of nature-inspired ingredients and cutting-edge technology holds immense promise for driving innovation in skincare. By harnessing the inherent bioactivity and adaptability of seaweeds, the cosmetic industry can develop novel formulations that deliver tangible results while also adhering to strict sustainability standards. This forward-thinking approach not only benefits consumers by providing them with efficacious skincare solutions but also contributes to the preservation of marine ecosystems and biodiversity. In essence, seaweeds, with their vast reservoir of bioactive compounds, represent a veritable treasure trove for the skincare industry. Their unique blend of natural goodness and scientific potential holds the key to revolutionizing skincare, offering a harmonious fusion of nature, science, and sustainability in the pursuit of radiant and resilient skin. As research continues to uncover the myriad benefits of seaweed-derived ingredients, the future of skincare looks brighter than ever, promising a healthier, more sustainable approach to beauty for generations to come.

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