Algae Metabolites in Cosmeceutical

Subjects: Dermatology

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Cosmeceuticals are topical cosmetic-pharmaceutical hybrids which refer to a cosmetic product with active ingredients claiming to have medicinal or drug-like benefits to skin health. Marine algae are rich in bioactive substances that have shown to exhibit strong benefits to the skin, particularly in overcoming rashes, pigmentation, aging, and cancer.

Keywords: marine algae ; cosmeceuticals ; UV-radiation ; anti-aging ; anticancer ; skin whitening

1. Introduction

1.1. Synthetic Versus Natural Ingredients in Cosmetic Industry

Cosmeceuticals are topical cosmetic-pharmaceutical hybrids which refer to a cosmetic product with active ingredients claiming to have medicinal or drug-like benefits to skin health [1][2]. Globally, the cosmeceutical industry is growing each year due to the trend of modern lifestyle. More recently, the cosmeceutical industry is progressively shifting to natural bioactive ingredients because of the ineffectiveness of synthetic cosmetics [3].

Ineffectiveness of synthetic cosmetics includes their side effects and low absorption rate. The low absorption rate of cosmetics could be due to the big size of the molecular compounds. A study by Bos and Marcus [4] asserted that only compounds with the molecular weight lesser than 500 Dalton (Da) could penetrate through the skin. Cyclosporin (MW 1202 Da), a topical immunosuppressant, was not effective against psoriasis and allergic contact dermatitis as a higher molecular weight of the compounds inhibits skin penetration. Still, it was effective in psoriasis treatment when directly injected into the skin. Some of the side effects include irritation and allergic reaction to the users. According to a case study, hydroxybenzoic acid esters (parabens), which are widely used in cosmetic products, has been reported to mimic oestrogen; hence, increasing the incidence of breast cancer and causing the development of malignant melanoma [5].

In addition, a study on a population conducted by the Centers for Disease Control and Prevention reported that 97% of 2540 individuals were exposed to phthalates (a component of plastic that appears in cosmetic products; for instance, dibutyl phthalate in nail polish), which could result in DNA damage in human sperm [6]. In 2004, the Environment California, Environmental Working Group, and Friends of the Earth issued reports on cosmetic products containing chemical ingredients that lacked safety data. Some of these chemicals caused adverse effects in animal studies such as male genitalia congenital disabilities, altered pregnancy outcomes, and decreased in sperm counts [6]. As a result, consumers have changed their preference and opted for natural cosmetic products. The global market value for natural cosmetics was about $34.5 billion in 2018, and it is estimated to reach approximately $54.5 billion in 2027 [7]. The ever-expanding market for skincare products and continual search for innovative ingredients has led to the development of a multitude of cosmeceutical products based on natural bioactive ingredients, which include plants, herbs, and even marine algae [8].

Macroalgae are classified into three major classes, namely Phaeophyceae (brown algae), Rhodophyceae (red algae), and Chlorophyceae (green algae). Based on the total culture production, it is estimated that about 59% of brown algae, 40% of red algae, and less than 1% of green algae are produced worldwide [9]. Marine algae are rich sources of structurally diverse bioactive compounds, which are absent in other taxonomic groups. Algae contain 10 times greater diversity of compounds than terrestrial plants [10] and they have a totally different flavonoid composition from vegetables and fruits. Macroalgae are a rich source of catechins and flavonols [11]. Furthermore, algae-derived phlorotannin possesses a unique structure, which is not found in terrestrial plants and this compound may constitute up to 25% of the dry weight of brown algae [11]. Algae produce a wide array of primary metabolites, such as unsaturated fatty acids, polysaccharides, vitamins, and essential amino acids [12][13]. Additionally, many research findings reported that secondary metabolites derived from algae such as fucoidan, fucoxanthin, sulphated polysaccharide, polyphenol and fucosterol were shown to possess anti-inflammation, antioxidant, anticancer, antibacterial and anti-aging effects [14][15][16][17][18]. The demand for algae bioactive compounds in cosmeceuticals is rapidly increasing as they contain natural extracts which are considered safe; thus, rendering fewer side effects on humans. In ancient times, marine algae were used as medicine to treat skin-related diseases, such as atopic dermatitis and matrix metalloproteinase (MMP) related disease [12]. In a nutshell, marine algae are a promising resource for the development of cosmeceuticals.

Marine algae can survive in harsh conditions (i.e., withstand heat, cold, ultra-violet radiation, salinity, and desiccation) [8][9][19] due to their ability to adapt to physiological changes by producing stress tolerant substances. For example, algae produce organic osmolytes during stress conditions, which also act as antioxidants and heat protectants. Algae grow under desiccation by producing specialized spores which remain dormant during stress conditions and revive once the conditions return to normal. The presence of thick cell walls with protective layers of chemical substances and mucilage sheath helps to delay the process of desiccation. Algae that grow in cold desserts can endure the subzero temperature and protect the cells from UV irradiation by producing spores that have thick cell walls and reserve food as lipid and sugars [20]. In addition, marine algae uptake inorganic ions to balance extracellular ion concentration and produce organic osmolytes which protects them from desiccation and UV lights. A study reported that *Dunaliella salina* has 55 novel membrane-associated proteins that showed changes in the composition and structure of the membranes associated with algae adaptation to salinity [21]. Algae are rich in a wide variety of secondary metabolites to help them adapt and survive in harsh conditions. Algae could also adapt to desiccation stress by producing specialized spores such as aplanspores, which are rich in astaxanthin. Astaxanthin is a carotenoid that protects the cells from photo-oxidation. Algae exposed to UV radiations will produce UV screening compounds such as mycosporine-like amino acids (MAA), which acted as antioxidants and involved in osmotic regulations. Furthermore, algae exposed to high solar radiation and low nitrogen concentration produce more β-carotene, such as *Dunaliella* [20]. Thus, algae that are naturally exposed to oxidative stress develop defense systems that protect them against reactive oxygen species (ROS) and free radicals. These compounds could be used in cosmetics to protect the cells against the adverse effects of UV radiation. Some of the environmental benefits of algae include fixation of carbon dioxide. Studies have reported that large cultivation of microalgae capable of uptaking carbon from the atmosphere; for instance, *Spirulina platensis* with carbon fixation rate of 318 $mg/L^{-1}d^{-1}$ and *Chlorella vulgaris* with carbon fixation rate of 251 $mg/L^{-1}d^{-1}$ [22][23].

1.2. Current Applications of Algae-Derived Metabolites in Cosmeceutical Industrial

The transition from synthetic compounds to natural products such as marine algae have been attracting the attention of many researchers since algae possess a wide range of pharmacological activities with negligible cytotoxicity effects in human cells [24]. Marine algae are used for different purposes in food, pharmaceutical, biofuel, agriculture, and cosmetic industries. Industries, such as Cyanotech, Fuji Chemical Seambiotic, and Mera Pharmaceuticals are producers of microalgae biomass contributing to products in pharmaceuticals, cosmetics, and nutritious feed [25]. Interestingly, phycocyanin (usually found in red algae and cyanobacteria) is accepted as a natural color additive in food and cosmetics by the Food and Drug Administration (FDA) due to its non-toxic, natural, and biodegradable properties. Accordingly, it becomes the major target of the market in the United States [26].

Meanwhile, carotenoid such as astaxanthin plays a crucial role in scavenging free radicals in the human body and it is considered a strong antioxidant; hence, its popularity as a human dietary supplement. Leading cosmeceutical industries, such as Unilever, L’Oreal, Henkel, and Beiersdorf are expected to improve the growth of carotenoid market value in the European market [27]. The market value for carotenoids is expected to reach about $1.53 billion by 2021 [27][28].

Furthermore, red algae *Gracilaria* account for most of the raw material for the agar extraction. It is reported by the Food and Agriculture Organization (FAO) of the United Nations that more than 80% of the agar were produced from *Gracilaria* species, which are mainly produced by China and Indonesia [29]. *Gracilaria* species have been widely used in cosmetics due to their stabilizing, thickening, and gelling characters. Commercially available products from *Gracilaria* species include hydrogel soap by Sea Laria®, facial mask by Balinique®, and hydrating cream by Thalasso® [29].

A number of algae-based skin products have been marketed, such as Algenist (an anti-aging moisturizer containing microalgae oil and alguronic acid from algae) [30], Helionori® by Gelyma and Helioguard365® (a sunscreen product containing MAAs from red seaweed *Porphyra umbilicalis*) [31], Protulines® by Exsymol S.A.M., Monaco (an anti-aging agent from protein-rich extract of *Arthrospira*), and Dermochlorella by Codif, St. Malo, France (an anti-wrinkling agent from *Chlorella vulgaris* extract) [32]. Therefore, bioactive compounds derived from algae could be considered a potential cosmeceutical agent for skincare.

1.3. UV Radiation and Skin-Related Diseases

Skin is one of the most complex and largest organs that serves as a protective barrier against water losses and environmental stresses, such as ultraviolet radiation (UVR), pathogens, physical agents, and chemicals [33]. The skin comprises three layers—epidermis, dermis, and hypodermis. The presence of keratinocyte cells and melanocyte cells in the epidermis layer plays a vital role in repairing damaged skin and protecting the skin from UV light. The dermis consists of elastin, hyaluronic acid, and collagen which involves tissue repair and stability, whereas hypodermis consists of fats, which involved in body insulation [9]. Several skin-related diseases that have been reported include acne, eczema, dermatitis, hives, psoriasis, and pityriasis rosea which cause rashes [34]. Other skin diseases include pigmentation disorders, such as hypopigmentation due to the absence of melanocytes and hyperpigmentation caused by a metabolic disorder or skin irritation. In addition, one of the biggest concerns is skin cancers (e.g., squamous, basal, and melanoma) with melanoma being the deadliest form in America because of overexposure to UV radiation [35].

In most cases, humans are exposed to UV radiation due to overexposure to sunlight. UV radiation can produce many adverse effects within the cells, including DNA damage, skin pathologies, such as erythema and inflammation, skin aging, and cancer [36]. There are three main components of UV radiation, namely UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm) [37]. UVA can reach the dermis layer of skin, increasing the level of ROS that indirectly induce DNA mutagenesis, which results in skin aging and wrinkling. UVA can act as a carcinogen by shortening telomere in the DNA strand and it has less ability to stimulate melanin production resulting in redness, sun tanning, and freckles. UVB can penetrate the epidermis layer and damage the DNA in skin cells directly and induce skin cancers. UVC is highly bioactive but humans are not exposed to UVC because it is mostly absorbed by the ozone layer. In addition, UV-induced oxidative stress plays a crucial role in causing aging, inflammation, melanogenesis and even cancer which are shown in **Figure 1** [9][12][38][39][40][41].

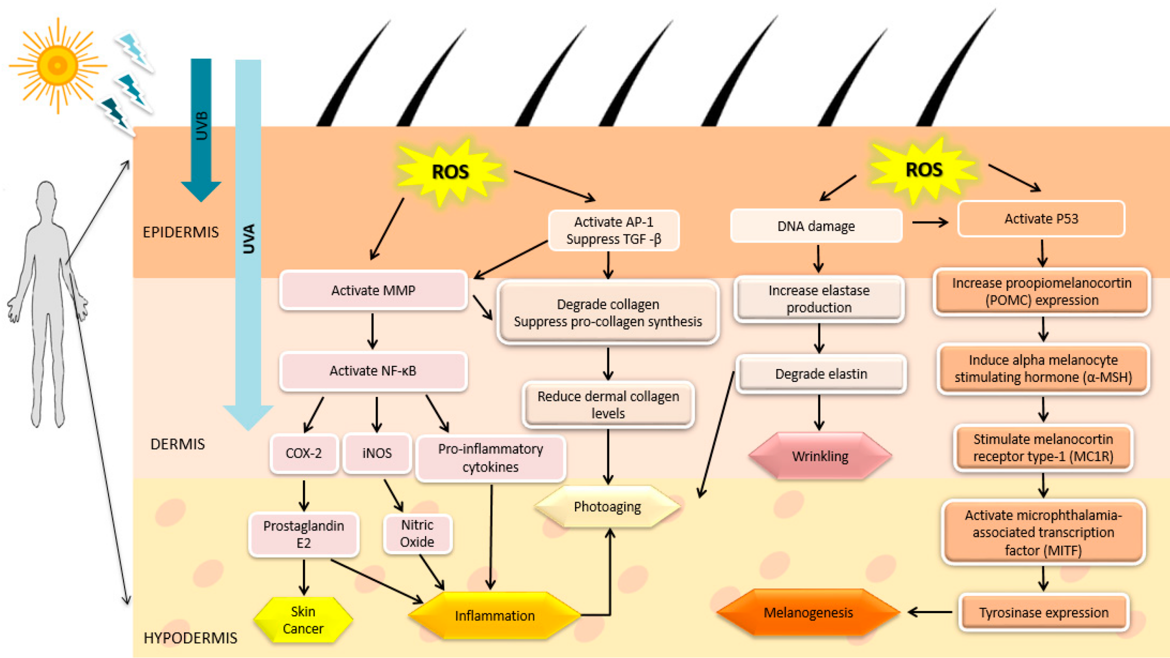
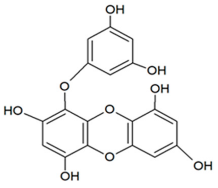


Figure 1. Effect of UV radiation-induced reactive oxygen species (ROS). Accumulation of ROS leads to skin cancer, inflammation, photoaging, wrinkling, and melanogenic through activation of respective signaling pathways.

2. Marine Algae-Derived Compounds in Cosmeceutical Application

Based on the evidence from previous studies, brown algae contribute the most in cosmeceuticals. Some bioactive compounds from brown algae exhibit multiple cosmeceutical activities, including phlorotannin, which possesses several activities, such as anti-melanogenic, antioxidant, anti-inflammation, and anti-aging [12][42][43][44]. Likewise, fucoidan, a sulphated polysaccharide isolated from brown algae, contributes to anti-inflammation, anti-melanogenic and anticancer [45][46][47]. Fucoxanthin, a carotenoid isolated from brown, red, green and microalgae exhibit anti-melanogenic, anti-aging and antioxidant activities [48][49][50]. Mycosporine-like amino acids (MAAs), which are commonly found in red and green seaweeds, and microalgae also contribute to antioxidant, anti-inflammation, and anti-aging [51][52][53]. Other examples of bioactive compounds derived from algae, their applications and mode of actions in cosmeceuticals are presented in **Table 1**. The chemical structures of some prominent bioactive compounds are shown in **Figure 2**.



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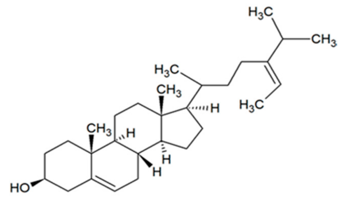

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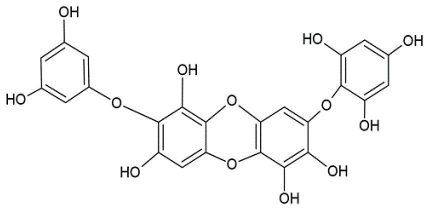

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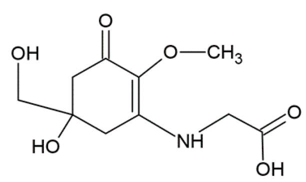

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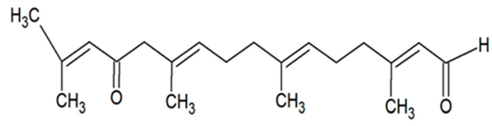

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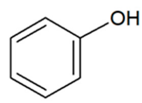

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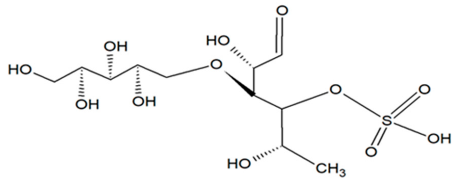

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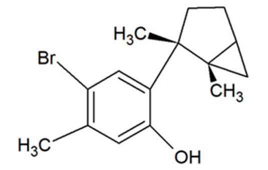

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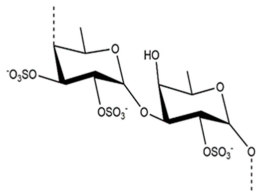

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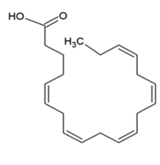

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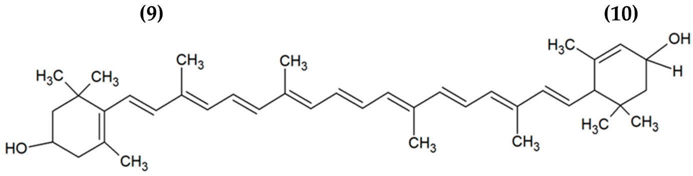

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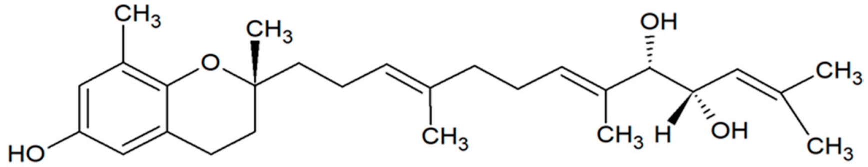

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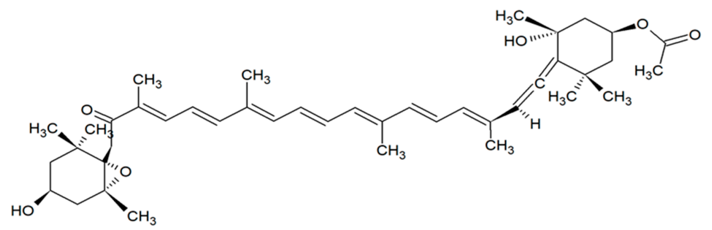

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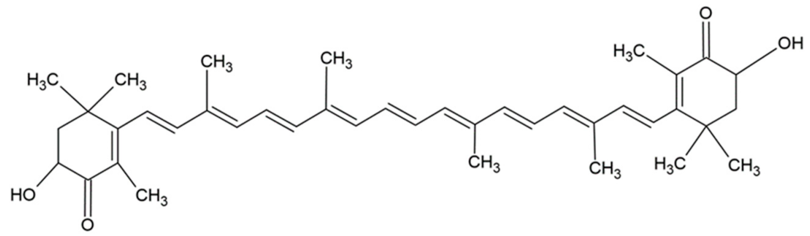

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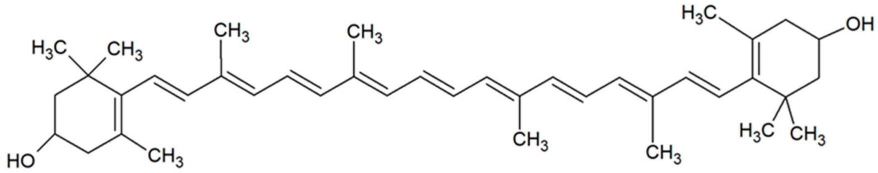

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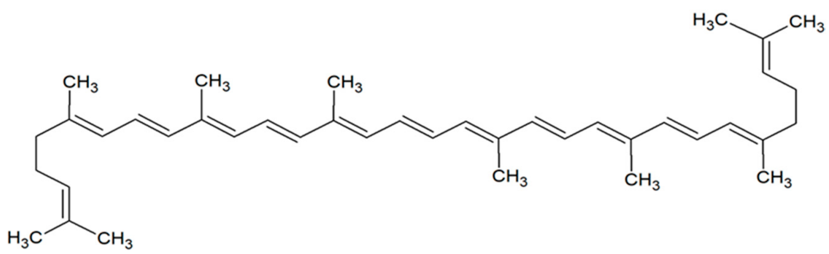

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Figure 2. Chemical structures of bioactive compounds derived from algae. (**1**) Eckol, (**2**) Fucosterol, (**3**) Diphlorethohydroxycarmalol, (**4**) Mycosporine-glycine, (**5**) Eleganonal, (**6**) Phenol, (**7**) Ascophyllan, (**8**) Laurinterol, (**9**) Fucoidan, (**10**) Eicosapentaenoic acid, (**11**) Lutein, (**12**) Sargachromanol E, (**13**) Fucoxanthin, (**14**) Astaxanthin, (**15**) Zeaxanthin, and (**16**) Lycopene.

Table 1. Bioactive compounds derived from algae and their applications in cosmeceuticals.

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
		Brown algae			
Ascophyllum nodosum	Ascophyllan	Anticancer	Inhibit MMP expression	B16 melanoma cells	[54]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Bifurcaria bifurcata	Eleganonal	Antioxidant	DPPH inhibition	*In vitro*	[55]
Chnoospora implexa	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*Staphylococcus aureus, Staphylococcus pyogenes*	[56]
Chnoospora minima	Fucoidan	Anti-inflammation	Inhibition of LPS-induced NO production, iNOS, COX-2, and PGE2 levels	RAW macrophages	[47]
Cladosiphon okamuranus	Fucoxanthin	Antioxidant	DPPH inhibition	*In vitro*	[49]
Colpomenia sinuosa	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Cystoseira barbata	Fat-soluble vitamin and carotenoids	Antioxidant	High fat-soluble vitamin and carotenoid content	*In vitro*	[57]
Cystoseira foeniculacea	Polyphenol	Antioxidant	DPPH inhibition (EC_{50} = 5.27 mg/mL)	*In vitro*	[58]
Cystoseira hakodatensis	Phenol and fucoxanthin	Antioxidant	High total phenolic and fucoxanthin content	*In vitro*	[59]
Cystoseira osmundacea	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. pyogenes*	[56]
Dictyopteris delicatula	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Dictyota dichotoma	Algae extract	Antimicrobial	Inhibit the synthesis of the peptidoglycan layer of bacterial cell walls	*Penicillium purpurescens, Candida albicans, Aspergillus flavus*	[60]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Ecklonia cava	Dieckol	Anti-inflammation	Suppression of iNOS and COX-2	Murine BV2 microglia	[61]
	Phlorotannin	Anti-melanogenic	Inhibit melanin production	B16F10 melanoma cells	[44]
	Phlorotannin	Antioxidant	ROS scavenging potential	Chinese hamster lung fibroblast (V79-4)	[62]
Ecklonia kurome	Phlorotannin	Anti-inflammation	Inhibit hyaluronidase	Assay of HAase (*In vitro*)	[42]
Ecklonia Stolonifera	Phlorotannin	Anti-aging	Inhibit MMP expression	Human dermal fibroblast cell	[43]
	Phlorofucofuroeckol A and B	Anti-inflammation	Inhibition of NO production by downregulating iNOS and prostaglandin E2	LPS stimulated RAW 264.7 cells	[63]
Eisenia arborea	Phlorotannin	Anti-inflammation	Inhibit release of histamine	Rat basophile leukemia cells (RBL-2HE)	[64]
Eisenia bicyclis	Phlorotannin	Anti-inflammation	Inhibit hyaluronidase	Assay of HAase (*In vitro*)	[42]
Fucus evanescens	Fucoidan	Anticancer	Inhibit cell proliferation	Human malignant melanoma cells	[45]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Fucus vesiculosus	Extract	Anti-aging	Stimulate collagen production	N/A	[8]
	Fucoidan	Anti-melanogenic	Inhibit tyrosinase and melanin	B16 murine melanoma cells	[46]
	Fucoidan	Anticancer	Decrease melanoma growth	Mice	[65]
	Fucoxanthin	Antioxidant	Prevent oxidation formation	*In vitro*, RAW 264.7 macrophage, Mouse (ex vivo)	[66]
Halopteris scoparia	Ethanol extract	Anti-inflammation	COX-2 inhibition	COX inhibitory screening assay kit	[67]
Himanthalia elongota	Fatty acid and Phenol	Antimicrobial	Bacterial growth inhibition	*Escherichia coli, Staphylococcus aureus*	[68]
Hizikia fusiformis	Fucosterol	Anti-aging	Inhibit MMP expression	Human dermal fibroblast	[18]
	Ethyl acetate extract	Anti-melanogenic	Inhibit tyrosinase and melanin	B16F10 mouse melanoma cells	[69]
	Fucoxanthin	Antioxidant	DPPH inhibition	*In vitro*	[70]
Hydroclathrus clathratus	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Ishige foliacea	Phlorotannin	Anti-melanogenic	Downregulation of tyrosinase and melanin synthesis	B16F10 cells Zebrafish embryo	[71][72]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Ishige okamurae	Diphlorethohydroxycarmalol	Anti-inflammation	Down-regulation of iNOS and COX-2 expression and NF-κβ activation	Human umbilical vein endothelial cells	[73]
Laminaria japonica	Fucoxanthin	Anti-melanogenic	Suppress tyrosinase activity	UVB- irradiated guinea pig	[48]
Laminaria ochroleuca	Polyphenol	Antioxidant	High total phenolic content and antioxidant capacity	*In vitro*	[74]
Macrocystis pyrifera	Phlorotannin	Antioxidant	ROS scavenging potential	*In vitro*	[8]
	Hyaluronic acid	Anti-aging	Enhance the production of syndecan-4	N/A	[75]
Padina concrescens	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Padina pavonica	Polyphenol	Antimicrobial	Bacterial growth inhibition	*Candida albicans* and *Mucor ramaniannus*	[17]
	Acetone extract	Antioxidant	Free radical scavenging activity (IC_{50} = 691.56 µg L^{-1})	*In vitro*	[60]
Padina tetrastromatic	Diterpenes	Antioxidant	DPPH (IC_{50} = 1.73) & ABTS (IC_{50} = 2.01) inhibitions	*In vitro*	[76]
	Sulfated polysaccharide	Anti-inflammation	COX-2 and iNOS inhibitions	Paw edema in rats	[77]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Petalonia binghamiae	Ethanol extract	Anti-melanogenic	Inhibit tyrosinase and melanin	B16F10 murine melanoma cells	[78]
	Aqueous extract	Antioxidant Anti-inflammation	DPPH inhibition COX-2 inhibition	*In vitro* *In vitro*	[67]
Rosenvingea intrincata	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Saccharina latissima	Phenol	Antioxidant	High total phenolic content, DPPH scavenging activity and FRAP	*In vitro*	[79]
Sargassum fulvellum	Fucoxanthin	Antioxidant	DPPH inhibition	*In vitro*	[70]
Sargassum furcatum	Methanol extract	Antioxidant	DPPH (EC_{50} = 0.461) & ABTS (EC_{50} = 0.266) inhibitions	*In vitro*	[80]
Sargassum hemiphyllum	Sulfated polysaccharide	Anti-inflammation	Inhibit LPS-induced inflammatory response	RAW 264.7 macrophage cells	[81]
Sargassum henslowianum	Sulfated polysaccharide	Anticancer	Activation of caspase-3	B16 melanoma cells	[82]
Sargassum horridum	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Sargassum horneri	Sargachromanol.E	Anti-aging	Inhibit MMP expression	UVA irradiated dermal fibroblast	[83]
	Alginic acid	Anti-inflammation	Inhibit inflammatory response	HaCaT cells	[84]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Sargassum muticum	Tetraprenyltoluquinol chromane meroterpenoid	Anti-aging	ROS scavenging potential	Human dermal fibroblast	[85]
Sargassum polycystum	Ethanol extract	Anti-melanogenic	Inhibit tyrosinase and melanin production	B16F10 melanoma cells	[39]
Sargassum serratifolium	Sargachromenol	Anti-melanogenic	Downregulation of microphthalmia-associated transcription factor	B16F10 melanoma cells	[39]
Sargassum siliquastrum	Fucoxanthin	Antioxidant	Reduced UVB-induced ROS production	Human fibroblast	[86]
Sargassum thunbergi	Thunbergols	Antioxidant	DPPH inhibition	*In vitro*	[87]
Sargassum vulgare	Methanol extract	Antioxidant	β-carotene bleaching activity	*In vitro*	[88]
Stoechospermum marginatum	Spatane diterpenoids	Anticancer	Cell growth inhibition	Murine B16F10 melanoma cells	[89]
Turbinaria conoides	Laminarin, alginate, fucoidan	Antioxidant	ROS scavenging potential	N/A	[33]
Turbinaria ornata	Fucoxanthin	Antioxidant	High FRAP value (>10 µM/µg of extract)	*In vitro*	[90]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Undaria pinnatifida	Fucoxanthin	Anti-aging	MMP expression reduction, VEGF	Mouse	[50]
	Ethyl acetate extract	Anti-melanogenic	Down regulate melanin and inhibit tyrosinase	Mouse B16 melanoma cells	[91]
	Polyunsaturated fatty acid	Anti-inflammation	N/A	Mouse ear edema and erythema	[92]
	Fucoxanthin	Antioxidant	DPPH inhibition	*In vitro*	[70]
		Red algae			
Alsidium corallinum	Methanol extract	Antimicrobial	Bacterial growth inhibition	*Escherichia coli, Klebsiella pneumoniae, Staphylococcus aureus*	[93]
Bangia	Algae extract	Antioxidant	Induce peroxidase and superoxide dismutase to reduce oxidative stress	*In vitro*	[94]
Bryothamnion triquetrum	Methanol extract	Antioxidant	DPPH (EC_{50} = 0.357) & ABTS (EC_{50} = 0.370) inhibitions	*In vitro*	[80]
Ceramium rubrum	Methanol extract	Antimicrobial	Bacterial growth inhibition	*Escherichia coli, Enterococcus faecalis, Staphylococcus aureus*	[93]
Chondrocanthus acicularis	Methanol extract	Antimicrobial	Bacterial growth inhibition	*E. coli, K. pneumoniae, E. faecalis, S. aureus*	[93]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Chondrus canaliculatus	Polysaccharide	Antioxidant	DPPH inhibition	*In vitro*	[95]
Chondrus crispus	Aqueous extract	Antimicrobial	Bacterial growth inhibition	*Salmonella Enteritidis*	[96]
Corallina pilulifera	Methanol extract	Anti-aging Antioxidant	Reduce the expression of gelatinase Inhibit free radical oxidation	Human dermal fibroblast Human fibrosarcoma (HT-1080)	[97]
Corallina vancouverensis	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Ganonema farinosum	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Gelidium crinaale	Fat-soluble vitamin and carotenoids	Antioxidant	High fat-soluble vitamin and carotenoid content	*In vitro*	[57]
Gelidium robustum	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Gracilaria gracilis	Phenol	Antioxidant	ROS scavenging potential	*In vitro*	[98]
Gracilariopsis lemaneiformis	Sulfated polysaccharide	Antioxidant	DPPH, Superoxide radical assay, hydroxyl radical assay (EC_{50} = 2.45 mg/mL)	*In vitro*	[99]
Gracilaria salicornia	2H- chromenyl	Antioxidant Anti-inflammation	DPPH and ABTS inhibitions COX-1 inhibition	*In vitro*	[100]
Jania rubens	Glycosaminoglycan	Anti-aging	Collagen synthesis	Unknown	[75]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Laurencia caspica	Phenol Ethanol extract	Antioxidant Antimicrobial	DPPH inhibition Bacterial growth inhibition	*In vitro* *Klebsiella pneumonia, Pseudomonas aeroginosa*	[101]
Laurencia luzonensis	Sesquiterpenes	Antimicrobial	Bacterial growth inhibition	*Bacillus megaterium*	[12]
Laurenicia obtusa	Polysaccharide	Antioxidant	DPPH (IC_{50} = 24 µg/mL), FRAP (IC_{50} = 92 µg/mL), Hydroxyl radical scavenging activity (IC_{50} = 113 µg/mL)	*In vitro*	[102]
Laurenicia pacifica	Laurinterol	Antimicrobial	Bacterial growth inhibition	*Staphylococcus aureus*	[9]
Laurencia rigida	Sesquiterpenes	Antimicrobial	Bacterial growth inhibition	*Bacillus megaterium*	[12]
Meristotheca dakarensis	Glycosaminoglycan	Anti-aging	Collagen synthesis	Unknown	[75]
Osmundaria obtusilo	Methanol extract	Antioxidant	DPPH (EC_{50} = 0.041 mg/mL), ABTS (EC_{50} = 0.031 mg/mL), Metal chelating (EC_{50} = 0.1 mg/mL), folin ciocalteu (EC_{50} = 0.128 mg/mL)	*In vitro*	[80]
Palisada flagellifera	Methanol extract	Antioxidant	β-carotene bleaching activity	*In vitro*	[88]
Palmaria palmata	MAA	Anti-aging	Collagenase inhibition	*Clostridium histolyticum*	[53]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Polysiphonia howei	Fucoxanthin	Antioxidant	High FRAP value (>5 µM/µg of extract)	*In vitro*	[90]
Porphyra haitanensis	Sulfated Polysaccharide	Antioxidant	ROS scavenging potential	Mice	[103]
Porphyra umbilicalis	MAA	Anti-aging	Control expression of MMP	Human dermal fibroblast	[16]
Porphyra sp.	MAA	Anti-aging	Collagenases inhibition	*Clostridium histolyticum*	[53]
Porphyra yezoensis	MAA Polyphenol Phycoerythrin	Antioxidant Anticancer Anti-inflammation	ROS scavenging potential and MMP expression Induce apoptosis Suppression of mast cells	Human skin fibroblast HaCaT cells Rat	[51]
Pterocladia capillacea	Sulfated polysaccharide	Antimicrobial	N/A	*Staphylococcus aureus* *Escherichia coli*	[104]
Pyropia columbia	Phenol	Antioxidant	DPPH, β-carotene bleaching and ABTS inhibitions	*Piaractus mesopotamicus*	[105]
Pyropia yezoensis	Polysaccharide	Anti-aging	Promote collagen synthesis	Human dermal fibroblast	[106]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Rhodomela confervoides	Polyphenol	Antimicrobial	Bacterial growth inhibition	*Candida albicans* *Mucor ramaniannus*	[17]
	Bromophenol	Antioxidant	DPPH inhibition	*In vitro*	[107]
Schizymenia dubyi	Phenol	Anti-melanogenic	Inhibit tyrosinase activity	*In vitro*	[39]
		Green algae			
Bryopsis plumose	Polysaccharide	Antioxidant	ROS scavenging potential	*In vitro*	[108]
Chaetomorpha antennia	Fucoxanthin	Antioxidant	DPPH inhibition (63.77%)	*In vitro*	[109]
Chlamydomonas hedleyi	MAA	Antioxidant Anti-aging Anti-inflammation	ROS scavenging potential Increase UV-suppressed genes (procollagen C proteinase enhancer and elastin) expression Reduce COX-2 and involucrin expression	*In vitro* HaCaT cells HaCaT cells	[52]
Cladophora sp.	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Codium amplivesiculatum	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Codium cuneatum	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Codium fragile	Sterol	Anti-inflammation	Reduces the expression of COX-2, iNOS, and TNF-α	Mice	[110]
Codium simulans	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, S. pyogenes*	[56]
Entromorpha intestinalis	Chloroform and methanol extract	Antioxidant	SOD activity is reduced	*Labidochromis caeruleus*	[111]
Enteromorpha linza	Polysaccharide	Antioxidant	ROS scavenging potential	*In vitro*	[108]
Gayralia oxysperma	Fucoxanthin	Antioxidant	High FRAP value (>6 μM/μg of extract)	*In vitro*	[90]
Ulva dactilifera	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*S. aureus, Streptococcus pyogenes*	[56]
Ulva fasciata	Fucoxanthin	Antioxidant	DPPH inhibition (83.95%)	*In vitro*	[109]
Ulva lactuca	Phycocolloids	Anti-inflammation	N/A	N/A	[75]
Ulva pertusa	Polysaccharide	Antioxidant	ROS scavenging potential	*In vitro*	[108]
Ulva prolifera	Phenol and flavonoid	Antioxidant	DPPH inhibition, high phenolic and flavonoid contents	*In vitro*	[112]
Ulva rigida	Phenol	Antioxidant	DPPH inhibition	*In vitro*	[113]
Ulva sp.	Sulfated polysaccharide	Anti-aging	Increase hyaluronan production	Human dermal fibroblast	[114]
		Microalgae/Cyanobacteria			

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Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Anabaena vaginicola	Lycopene	Antioxidant Anti-aging	N/A	*In vitro*	[115]
Arthrospira platensis	Methanol extracts of exopolysaccharides	Antioxidant	N/A	*In vitro*	[115]
Chlorella fusca	Sporopollenin	Anti-aging	Protect cells from UV radiation	N/A	[116]
Chlorella minutissima	MAA	Anti-aging	Protect cells from UV radiation	N/A	[116]
Chlorella sorokiniana	MAA	Anti-aging	Protect cells from UV radiation	N/A	[116]
	Lutein	Anti-aging	Reduce UV induced damage	N/A	[33]
		Anti-aging	Reduced activity of SOD	Human diploid fibroblast	[117]
Chlorella vulgaris	Hot water extract	Anti-inflammation	Downregulated mRNA expression levels of IL-4 and IFN-γ	NC/Nga mice	[118]
	β-carotene	Antioxidant	Protect against oxidative stress	Rat	[119]
Dunaliella salina	β-cryptoxanthin	Anti-inflammation	Reduced the production of IL-1*β*, IL-6, TNF-*α*, the protein expression of iNOS and COX-2	LPS-stimulated RAW 264.7 cells	[120]

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Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
Haematococcus pluvialis	Astaxanthin (carotenoid)	Anti-aging	Inhibit MMP expression	Mice and human dermal fibroblasts	[121]
		Anticancer	ROS scavenging potential	Mice	[122]
Nannochloropsis granulata	Carotenoid	Antioxidant	DPPH inhibition	*In vitro*	[123]
Nannochloropsis oculata	Zeaxanthin	Anti-melanogenic	Inhibit tyrosinase	***In Vitro***	[124]
Nitzschia sp.	Fucoxanthin	Antioxidant	Reduced oxidative stress	**Human Glioma Cells**	[125]
Nostoc sp.	MAA	Antioxidant	ROS scavenging potential	*In vitro*	[126]
Odontella aurita	EPA	Antioxidant	Reduce oxidative stress	Rat	[127]
Planktochlorella nurekis	Fatty acid	Antimicrobial	Bacterial growth inhibition	*Campylobacter jejuni, E. coli, Salmonella enterica var.*	[128]
Porphyridium sp.	Sulfated polysaccharide	Anti-inflammation	Inhibit proinflammatory modulator	Unknown	[103]
		Antioxidant	Inhibited oxidative damage	3T3 cells	
Rhodella reticulata	Sulfated polysaccharide	Antioxidant	ROS scavenging potential	*In vitro*	[103]
Skeletonema marinoi	Polyunsaturated aldehyde and fatty acid	Anticancer	Inhibit cell proliferation	Human melanoma cells (A2058)	[129]

Algae Species	Bioactive Compound/Extract	Beneficial Activity	Mechanism of Action	Experimental Model	Reference
	β-carotene and phycocyanin	Antioxidant Anti-inflammation	Inhibit lipid peroxidation Inhibit TNF-α and IL-6 expressions	Mouse Human dermal fibroblast cells (CCD-986sk)	[130]
Spirulina platensis	Ethanol extract	Antimicrobial	Bacterial growth inhibition	*E. coli, Pseudomonas aeruginosa, Bacillus subtilis* and *Aspergillus niger*	[131]
Synechocystis spp.	Fatty acids and phenols	Antimicrobial	Bacterial growth inhibition	*E. coli and S. aureus*	[68]

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