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Algal Technologies and Phytochemicals Bioactive Ingredients for Applications in Nutrition and Medicine: A Review

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ABSTRACT

This review highlights the substantial nutritional worth of seaweeds by examining their nutritional content and bioactivity. Seaweeds provide several health advantages, including cardio-protection, anti-tumor, anti-oxidative, antibacterial, anti-inflammatory, and immunostimulatory properties owing to their high content of polysaccharides, proteins, PUFAs, minerals, and bioactive chemicals. Bodybuilders love them because they are high in fiber and low in calories. Seaweeds are an interesting target for drug development because of their potential use in medicine and disease prevention. Nonetheless, a number of seaweeds remain underutilized, and further research on seaweed extracts is essential. For effective usage, further knowledge of bioactivity and mechanisms of action is also required. Seaweeds may also be used as fertilizer and biofuel.

REVIEW

Seaweeds, or macroalgae, are marine thalli that contribute to half of Earth's primary production and are used in various industries like food, feed, and fertilizer **(Mohammad *et al.*, 2019).** They are rich in minerals, fiber, protein, vitamins, and bioactive compounds, making them a nutrient-dense, low-calorie superfood **(Shama *et al.*, 2019)**. As sustainability and health concerns grow, there is an increasing interest in developing seaweed farms in Western nations **(Wells *et al.*, 2017; Blikra *et al.*, 2019)**. Seaweeds, valuable marine plants, are gaining popularity due to their abundant minerals, fiber, protein, and vitamins. Seaweeds are a low-fat, low-calorie superfood with numerous health benefits, including antibacterial, antioxidant, anti-inflammatory, anti-cancer, and anti-obesity characteristics **(Kang *et al.*, 2020; El-Sheekh *et al.*, 2024)**. They contain natural secondary chemicals with similar protein levels to those from traditional sources **(Bleakley and Hayes 2017).** While seaweeds have many health advantages, there are also hazards, such as infections, poisoning, heavy metal accumulation, and pesticide residues. **Van der Spiegel *et al.* (2013)** found that they are vulnerable to pesticides and

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other micropollutants. Biological analysis can confirm that seaweeds are safe to eat; however, harvesting, storing, and processing techniques can affect their nutritional value **(Wells *et al.*, 2017)**. According to **Probst *et al.* (2015)**, legislative barriers impede the introduction of novel food sources, despite the necessity for regulations that define intake criteria to be introduced safely.

1. Seaweeds as a functional food; antioxidants and therapeutic bioproducts against some chronic diseases

Certain bioactive chemicals found only in seaweeds have been used for commercial purp oses (Kelman *et al*., 2012; Shama *et al*., 2019). These compounds have the capacity to provide health advantages (**Rengasamy *et al*., 2020**).

1.1. Phycoerythrin

Phycoerythrin, a valuable phycobiliprotein with numerous biological properties, has the potential to replace artificial dyes and be used as a natural dye (**Bungau *et al*., 2019**).

1.2. Dietary Fiber

Seaweeds, rich in soluble fibers like alginate, carrageenan, and agar, can reduce body weight by delaying stomach emptying, according to **Kristensen and Jensen (2011**).

1.3. Sulfated Polysaccharides

Fucus vesiculosus contains sulfated polysaccharides called fucoidans, which act as antioxidants and lower the chance of developing chronic illnesses like diabetes, dyslipidemia, and coronary heart disease **(Iso and Kubota, 2007; Cardoso et al., 2014).**

1.4. Carotenoids

Age-related macular degeneration, neurological conditions, and degenerative diseases are among the chronic illnesses that can be prevented by seaweed carotenoids, a natural source of antioxidants. They offer defense against oxygen species that are singlet (**Stahl and Sies, 2012)**, oxidative damage (**Abdali *et al.*, 2015**), together with inflammatory cells (**Seca and Pinto, 2018**). Multiple studies have demonstrated the superiority of seaweeds as a dietary supplement and medicinal agent (**Lordan *et al.*, 2011; Rodriguez-Concepcion *et al.*, 2018)**. Because they contain fatty acids, minerals, and peptides, they complement diets, inhibit pathogenesis, and improve physiological functioning (**Manerba *et al*., 2010).**

1.5. Vitamin and Mineral Composition and Benefits of Various Seaweed Species:

Bekah *et al*. (2023) concluded that the profiling of seaweeds collected around Mauritius and Rodrigues showed that they are a good source of retinol (vitamin A), beta-carotene (pro-vitamin A), ascorbic acid (vitamin C), and a few from the B-complex vitamin family. The vitamin concentration depended on the location where the sample was collected as well as on the species. The seaweed species analyzed are also good sources of minerals such as magnesium, calcium, and sulfur. Given that some of the seaweeds are already consumed, Vitamin B12 is a commonly red-colored vitamin and has the largest molecular mass (1355.4) and the most complex structure of all the vitamins **(Watanabe and Bito 2016).** B12 is synthesized only by certain bacteria and archaea but not by plants. Thus, animal-based foods, such as meat, milk, and fish, but not plant foods, are the primary dietary sources of B12 **(Watanabe 2007; Watanabe and Bito 2018).** Therefore, vegans, or strict vegetarians who cannot ingest any animal-based foods are reportedly at risk of developing B12 deficiency **(Pawlak *et al.* 2013).**

Seaweed stands out as the only plant capable of providing vitamin B12. The edible brown algae contain none or a trace amount of B12, such as *Laminaria angustata* (Kombu) and *Sargassum fusiformis* (Hijiki). On the other hand, a substantial amount of B12, at more than 30 μg/100 g dry weight, was found in some green algae, such as *Enteromorpha* spp. and *Ulva* spp., and red algae, such as *Porphyr*a spp. The genus *Porphyra* is widely consumed in Japan, Korea, and China **(Levine and Sahoo 2010).** Wild *Porphyra* spp. is harvested in these counties. On the other hand, *Porphyra tenera* and *Porphyra yesoensis* are cultivated in Korea and China, respectively **(Nui *et al*. 2010)**. Various species of *Porphyra* are most commonly consumed as packages of dried nori sheets that are available in Japan and Korea. Studies have been conducted to determine whether *Porphyra* spp. contains true B12 or inactive corrinoids. The B12 compound purified from various *Porphyra* sp. (purple lavers), was identified as B12 and not as the inactive pseudo-vitamin B12 (PseudoB12) found in humans **(Watanabe *et al.*, 1999b; 2000)**, which contains a substantial amount of B12 **(Watanabe *et al*. 1999a; 2002)**.

Muñoz and Nelson (2020) revealed that seaweeds are rich in essential minerals, with a mineral content at least 10 times higher than that of terrestrial plants. They contribute significantly to daily mineral intake and are a promising source of functional foods, food supplements, and nutraceuticals. They concluded that seaweeds can be used as food supplements for critical minerals and sustainable functional foods, potentially addressing global mineral shortages. Dry seaweed contains higher levels of essential minerals than other mineral-rich foods, providing significant RDAs or AIs. However, high levels of iodine, selenium, and chromium in some seaweed exceed recommended levels, potentially causing negative health effects.

1.6. Phyto-Sterols

With an emphasis on the prospective uses and health advantages of phytosterols generated from seaweed, **Sohn *et al*. (2023)** investigate the biosynthetic pathways and mechanisms of action of these compounds. Steroids, including cholesterol, stigmasterol, fucosterol, β-sitosterol, and campesterol, are found in seaweeds and may have a role in their advantageous biological properties. These bioactive sterols may have antioxidant, antibacterial, anticancer, and anti-inflammatory properties. Subsequent investigations ought to concentrate on enhancing phytosterols' bioavailability through structural and chemical adjustments. While physical modifications, such as nano-delivery devices, can boost oral bioavailability, chemical synthesis can increase fat solubility. These results may enhance the broad utilization of bioactive chemicals obtained from seaweed in biomedical settings.

2. Seaweed's impact on chronic illnesses

2.1. Obesity

Obesity is a global issue, with increasing risks of diseases like cardiovascular disease, osteoarthritis, hypertension, type 2 diabetes, and dyslipidemia (**Haslam and James, 2005**). Seaweed carotenoids, particularly fucoxanthin, can treat obesity-related disorders by reducing oxidative inflammatory conditions (**Ojulari *et al*., 2019**). FXN's anti-adiposity action is regulated by the nuclear receptors PPARγ and C/EBPα (**Lee *et al*., 2019**), which promote adipogenesis and insulin resistance (**Eeckhout *et al*., 2012**). PPARγ activation in adipocytes increases obesity-related insulin resistance, promotes adipogenesis, and regulates adipogenic genes, suggesting they upregulate their expression (**Siersbaek *et al*., 2010**).

Alginate bread aids weight management by extending the stomach and producing short-chain fatty acids during intestinal fermentation (**Hall *et al*., 2012**). Alginate-based drinks during an extended period of time reduce energy consumption in healthy, obese, overweight, and normal-weight individuals. A pilot trial showed that alginate-containing drinks improved energy intake and satiety in normal-weight individuals but not in obese patients on calorie-restricted diets. Fucoxanthin from brown seaweed decreases white fat tissue (**Georg Jensen *et al*., 2012**).

2.2. Diabetes type I

Fucoxanthin, polyphenolics, and phenolics found in seaweeds have anti-diabetic properties that lower the incidence of diabetes in underdeveloped countries (**Roberts 2010; Selassie and Sinha 2011**). Diseases can be kept from getting worse by a balanced diet and frequent exercise (**Ogurtsova *et al.*, 2017**).

Proteins, lipids, pigments, polysaccharides, and polyphenols found in seaweeds have been shown to have bioactive properties that may mitigate the risk of type 2 diabetes and slow its progression (**Holdt and Kraan, 2011; El Shafey *et al*., 2021**).

Seaweed bioactive components, such as alginate and fucoidan, have been found to positively impact glucose metabolism, reduce body weight, and decrease alpha-glucosidase activity in individuals with impaired glucose tolerance and diabetes (**Kim *et al*., 2012**).

Polyphenols found in brown algae as well as fucoidan, and dieckol have been shown to lower blood glucose, guard against oxidative stress brought on by glucotoxicity, and postpone the onset of type 2 diabetes (**Kang *et al*., 2013; Sakai *et al*., 2019**), lower postprandial hyperglycemia in prediabetes, and have anti-diabetic effects (**Apostolidis and Lee, 2010; Lee and Jeon, 2015**).

Quercetin flavonoid prevents insulin resistance in type 2 diabetes mice (**Jeong *et al*., 2012**), while fucoxanthin boosts cytokine production, lowers blood glucose levels, and improves insulin resistance by stimulating UCP1 in adipose tissue (**Mikami *et al*., 2017**).

Seaweeds can reduce cardiovascular disease risk factors and enhance insulin sensitivity, but not postprandial glucose levels in healthy individuals, as brown seaweed extracts improve glucose levels after carbohydrate-rich meals (**Keleszade *et al*., 2021**).

2.3. Cancer

Cancer, a major public health concern. In 2018, there were 9.6 million fatalities and 18 million new cases. Prompting research on marine seaweeds containing fucoxanthin's potential to combat it (**Satomi, 2017**).

Fucoxanthin, found in *Champiafeld mannii* and *Gracilaria lemaneiformis,* has been found to modulate cellular components and signal transduction pathways, potentially boosting immune and anti-cancer properties (**Yan *et al*., 2010; El-Kassas *et al*., 2014**; **Gheda *et al*., 2018**).

Red seaweeds, rich in polyphenolic compounds, have been found to suppress colon cancer by increasing the activity of antioxidant enzymes, effectively eliminating oxidative stress-associated colon carcinogenesis (**Waly *et al*., 2016**). Research indicates that seaweed consumption in Asians, particularly in premenopausal Korean women, can reduce cancer incidence compared to Western diets (**Ferlay *et al*., 2008; Yang *et al*., 2010; Iso, 2011**).

2.4. Cardiovascular diseases

Heart-related conditions, including CVDs, are predicted to cause 23.6 million deaths globally by 2030, accounting for 20% of deaths (**Gaziano, 2005; Alissa and Ferns, 2011**). Consuming seaweeds has been associated with a lower risk of cardiovascular disease, especially in Japanese men and women (**Cumashi *et al*., 2007**). The components of seaweeds, such as fucoxanthin, which is found in brown seaweeds, have been shown to have anticoagulant, platelet aggregation-inhibiting and anti-inflammatory properties (Liu *et al*., 2013). Patients with atherogenic dyslipidemia and ischemic heart disease have shown benefits from fucoxanthin, a substance present in seaweed oils, in terms of preventing atherosclerosis (**Ionov and Basova, 2003; Khan *et al.*, 2006**) by down-regulating LDL receptors and promoting expression of sterol regulatory element binding proteins (**Airanthi *et al*., 2011; Beppu *et al*., 2012**).

3. Seaweeds have benefits for human gut microbiome health.

Seaweeds have been demonstrated to reduce chronic illnesses, including cancer and cardiovascular disease, as well as increase good bacteria in the colon (**Winberg, 2015; El-Beltagi *et al*., 2022**). There is additional evidence that low-short-chain fatty acids support the development of the intestinal mucosa. *Ascophyllum* species of seaweeds are efficient prebiotic foods because of their high fiber content, omega-3 fatty acid content, and readily available vitamins and minerals (**Wells *et al*., 2017; Lopez-Santamarina *et al*., 2020**). Strong immune function and intestinal health are supported by a diet rich in whole, unprocessed foods (**Wu *et al*., 2012**).

Seaweeds are high in fiber, making up 25-75% of their dry weight. Sulfated polysaccharides in seaweed boost gut bacteria growth and short-chain fatty acid production, providing gut cell nourishment (**Penalver *et al*., 2020**).

Nori seaweed's carbohydrate may stimulate specific probiotic strains, potentially altering gut flora, according to Stanford University School of Medicine research, suggesting that eating seaweed may establish specific bacteria strains. Probiotics, like yogurt, support the digestive system by providing live, beneficial bacteria, while prebiotics nourish these bacteria for growth and function, preventing irritable bowels due to insufficient high-fiber food. Bacteria break down and absorb indigestible carbs and sugars in dairy products, potentially promoting health benefits due to variations in bioactive substances in seaweed species (**Liu *et al*., 2012**).

Research has indicated that seaweed-derived fibers and low-molecular-weight polysaccharides possess prebiotic properties, and marine-derived products are becoming more and more recognized as innovative prebiotic carbohydrates (**O'Sullivan *et al*., 2010; Ramnani *et al*., 2012).** According to **Ding and Shah's (2009)** research, probiotic life is enhanced by the physical barriers that carrageenan, xanthan, and alginate provide against unfavorable digestion conditions. Chitosan binds with alginate are possible delivery vehicles with antiviral qualities, as are sulfated polysaccharides present in certain seaweed species (**Islam *et al*., 2010**).

Carrageenans, fucoidans, and sulfated rhamnogalactans show significant antiviral activity against enveloped viruses like HIV and herpes, as revealed in animal research both in vitro and in vivo. Fucoidan has been found to inhibit the development of numerous viruses, as demonstrated by **Trinchero *et al.* (2009**). A clinical investigation in South Carolina, United States, found no harm in HIV-positive patients after three months of daily consumption of 5–6 g of brown seaweed. A 13-month trial found a significant improvement in CD4 cell counts and a drop in viral load in a participant without antiretroviral medication using Tasmanian *Undaria pinnatifida* extract (**Teas and Irhimeh, 2012**).

4. Recipes Featuring Seaweed for Food, Health-Related Uses, and Novel Products, Such as Meat and Meat Alternatives

Earth's land comprises 29%, water 71%, freshwater 3%, and marine 96%. Oceans house over 2.2 million species, with algae occupying the surface layer (**Mora *et al.*, 2011**), indicating sufficient surface area for photoautotrophic organisms. Seawater is utilized to cultivate over 30,000 marine species, restoring the ecosystem, an environmentally friendly material used in farming, and increasing farm output without environmental harm (**Layek *et al*., 2015; Gomez-Zavaglia *et al*., 2019**). Seaweed farming is a sustainable adaptation due to its ability to absorb and store CO_2 (**Chung *et al*., 2013**), with research on Costa Rica's Caribbean and Pacific coasts highlighting their impact on climate change (**Radulovich *et al*., 2015**). Seaweed farming is a lifesaver due to its surface water-growing ability and sustainable investment in reducing carbon emissions due to its ability to trap carbon, phosphate, and nitrogen **(Table 1 and Fig. 1)**. It aims to transform seaweed into nutrient-dense food sources (**Shama *et al*., 2019)**.

Asian cuisine traditionally uses edible seaweeds, particularly in Japan and Korea. Western gastronomy differs from Asian cuisine, with American and Canadian cuisines primarily supplying Asian foods from outside (**Penalver *et al.*, 2020)**. **Van den Burg *et al*. (2021)** found seaweed too foreign for France's European cuisine experiment, while **McHugh (2003)** noted the addition of 3% seaweed to expensive German and Austrian bread.

Seaweeds are becoming more and more known as a nutritious food item in Southeast Asian countries, including China, Korea, Japan, Malaysia, Thailand, Indonesia, and Philippines, because seaweeds are high in protein and fiber (**Penalver *et al*., 2018**). It is difficult to incorporate seaweed into regular cooking since its flavor and texture are still unknown. You can add flavor and creativity to bring forth their sensory aspects. Digital media, online recipes by well-known chefs, and sustainable resources have all contributed to the growing popularity of seaweeds, also known by many names in the food sector. A variety of seaweeds are widely included in recipes, such as winged kelp, wakame, mozuku, sea grapes, hiziki, Dulse, and *Gracilaria* spp. According to **Gomez-Zavaglia *et al.* (2019**), the most often used seaweeds in soup, salad, and curry recipes internationally are *Porphyra* sp., *Eucheuma* sp., *Undaria* sp., *Macrocystis* sp., *Sargassum* sp., *Ulva* sp., *Monostroma* sp., *Hydroclathrus* sp., *and Acanthophora* sp. Seaweeds possess strong biological properties, such as their ability to reduce inflammation and fight bacteria. According to **Pati *et al.* (2016)**, the Romans and Egyptians used them to treat skin conditions and breast cancer. According to archeological findings, at a site in southern Chile dating back 14,000 years, they were eaten after being partially cooked (**Tom *et al*., 2008**).

Sticky rice and raw fish were combined to make nori about 1500 years' ago. Seaweeds are very flavorful and spicy, which has kept Indians from utilizing them to their full potential (**Sumayaa and Kavitha, 2015**). Seaweeds are grown in Tamil Nadu and Kerala, eaten as porridge, and used subtly as stabilizers in culinary products including ice cream, chocolate, and jellies (**Dhargalkar and Verlecar, 2009**).

Research suggests that seaweeds can help prevent global issues like diabetes, obesity, cancer, osteoarthritis, and cardiovascular disease **(Brown *et al*., 2014).** The Gulf of Mannar's Mandapam coast in South India is a major seaweed-growing harbor (**Krishnan *et al*., 2015**).

Seaweed proteins, peptides, and amino acids range from 5% to 47% of their dry weight, depending on factors like algal species, season, and geographical location (**Jeon *et al*., 2011; Harnedy *et al*., 2013**). Chlorophyceae and Rhodophyceae have higher protein contents than Phaeophyceae (**Garcia-Vaquero *et al*., 2017**). Seaweed proteins are excellent sources of amino acids, and peptides with a wide spectrum of bioactivities can be obtained from the protein fraction extracted from marine seaweeds. Fluorescent proteins from Dalga *P. palmata* could be used to prevent hypertension due to their ACE inhibitor activity **(Sepulveda *et al*., 2013**).

Table 1. Bioactive substances found in seaweeds and their activity.

Seaweeds bioactive compounds	Algae Species	Bioactivity	Reference
Fucoidan	***Chnoospora minima*** (Hering) Papenfuss ***Fucus evanescens*** C.Agardh ***Sargassum fulvellum*** (Turner) C.Agardh ***Dictyota dichotoma*** (Hudson) J.V. Lamouroux	Anti-inflammation Anti-cancer Anticoagulant action both *in vitro*and *in vivo* Antioxidant, anti-inflammatory, anticoagulant, anticancer, and antibacterial properties Antioxidant, and antitumor	**Hwang *et al*., 2011.** **Anastyuk, *et al*., 2012.** **Drozd *et al*., 2006.** **Millet *et al*., 2011.** **El-Sheekh *et al*., 2023.**
Fucoxanthin	***Cladosiphon okamuranus*** Tokida *Laminaria japonica* Areschoug ***Gayralia oxysperma*** (Kützing) K.L.Vinogradova ex Scagel & al. ***Ulva fasciata*** S.F.Gray ***Sargassum horneri*** (Turner) C.Agardh	Antioxidant Anti-melanogenic Antioxidant Antioxidant Anti-proliferative	**Mis e *et al*., 2011** **Shimoda *et al*., 2010** **Kelman *et al*., 2012** **Premalatha *et al*., 2011** **Sangeetha *et al*., 2009**
Phenols	***Saccharina latissima*** (Linn.) C.E.Lane, C.Mayes, Druehl & G.W.Saunders ***Schizymenia dubyi*** (Chauvin ex Duby) J.Agardh	Antioxidant *In vitro* Anti-melanogenic	**Sappati *et al*., 2019** **Azam *et al*., 2017**
Polysaccharides	***Bryopsis plumosa*** (Hudson) C.Agardh ***Ulva pertusa*** Kjellman ***Sargassum fulvellum*** (Turner) C.Agardh ***Laurencia papillosa*** (C.Agardh) Greville	Antioxidant Antioxidant, anti-inflammatory, anticoagulant, anticancer, and antibacterial properties hyperglycemic activity	**Zhang *et al*., 2010** **Millet *et al*., 2016** **El-Sheekh *et al*., 2024**
Ulvan	***Ulva lactuca*** Linnaeus ***Ulva*** spp.	Antifungal against some food borne fungi Immunomodulatory, Antioxidant, Anticancer, and Pharmacokinetic Activity	**El Fayoumy *et al*., 2022** **Pradhan *et al*., 2023**
Alginate	***Sargassum latifolium*** (Turner) C.Agardh	Antibacterial activity	**El-Sheekh *et al*., 2022.** **Hussein *et al*., 2021.**

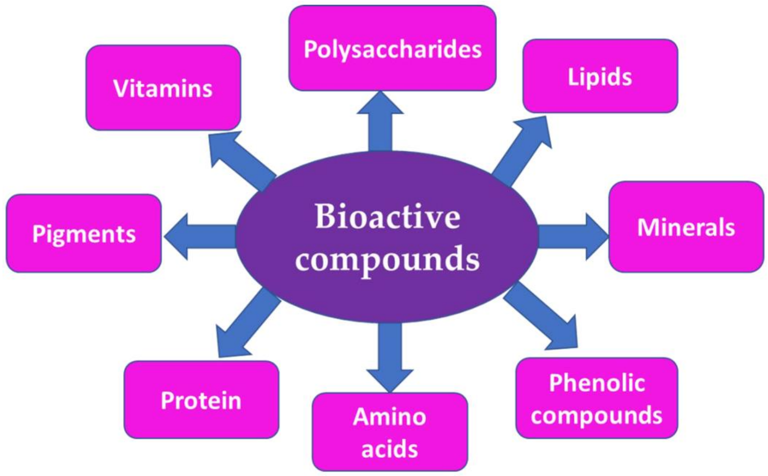

Fig. 1. Main bioactive compounds from marine seaweeds (El-Beltagi *et al*., 2022).

The Food and Agricultural Organization (FAO) predicts that Europe will require 56 million metric tons of protein by 2054 **(FAO, 2018).** Seaweed-derived proteins could be a viable solution, as they are sustainable, highly nutritious, and don't require land for cultivation (**Morais *et al*., 2020**). Seaweeds have a protein content of 8–47% dry weight, with red and green species having the highest content **(Garcia-Vaquero and Hayes, 2015)**. Some seaweeds have a higher protein content than traditional sources like milk. However, if ingested in large quantities, bioactive chemicals found in seaweeds may have antinutritional consequences. Seaweeds can grow in environments unsuitable for other plants or vegetation and are rich in phytochemicals, essential vitamins, and amino acids (**Garcia-Vaquero and Hayes, 2017**). Seaweeds are a valuable protein source, rich in phytochemicals, essential vitamins, and amino acids, making them a sustainable resource for dietary health (**Peñalver *et al*., 2020**). As "climate-friendly" protein sources, seaweeds may help achieve the UN's 2030 target of ending world hunger **(FAO, 2020).** They can be found in microbiological ingredients such as pasta, bread, salads, vitamins, and weight agents. In addition, they are utilized in mayonnaise and egg substitute goods, as well as meat substitutes for burgers and patties (**Brien *et al*., 2022**).

5. Food Industry Uses of Marine Algal Colorants.

Phycobiliproteins, carotenoids, and chlorophylls are the three kinds of pigments found in marine seaweeds. Carotenoids are soluble compounds with distinct protein structures that are soluble in water, whereas chlorophylls are green, fat-soluble pigments used in photosynthesis. Food coloring, nutraceutical components, and biological agents are among the uses for phycobiliproteins, which include red and blue pigments. According to **Yan *et al.* (2014**), these pigments also exhibit immunomodulatory, antioxidant, antiangiogenic, anticancer, and anti-inflammatory qualities.

Seaweeds are marine algae with varying pigment structures that give them a red, brown, or green appearance (**Silva *et al*., 2020**). These are present in complex ecosystems and are affected by temperature, salinity, light, pollutants, and nutrients, as stated by **Schmid *et al*. (2017)** and **Marinho-Soriano (2012)**. According to **Cotas *et al*. (2020; Aryee *et al*., 2018)**, seaweeds provide bioactive substances such as secondary metabolites, including peptides, phenolic compounds, halogenated chemicals, sterols, and terpenes. Antioxidant, anticancer, anti-inflammatory, and antibacterial properties are attributed to these pigments, which also include phycobiliproteins, carotenoids, and chlorophylls (**Aryee *et al*., 2018**). Stabilizers and stiffeners are applications for extracted seaweed in several manufacturing sectors. Because they are used in the nutraceutical industry, seaweeds are economically important because of their high molecular weight polysaccharides (**Wiencke and Bischof, 2012**).

Algal biomass is collected using a variety of methods in order to extract chlorophylls that is utilized in industrial appliances. Phycobilins are water-soluble pigments that are removed from fat using organic solvents, including methanol, acetone, and DMSO. Carotenoids and chlorophylls are dissolved by fat. The algal biomass is homogenized and extracted using a natural solvent (**Hosikia *et al*., 2010**). Heat, light, oxygen, and a high pH can also be used to remove seaweed pigments before they are destroyed. Pigments are extracted with organic solvents, and polysaccharides are released when cellular membranes are broken down and thawed. Diverse extraction techniques have been used to process the whole biomass with no waste (**Aryee *et al*., 2018**).

To extract minerals, *Gracilaria corticata* was used to produce fats, agar, pigments, and bioethanol. An appropriate solvent and aqueous extraction technique were also created (**Hessami *et al*., 2019**). The freeze-drying method extracts pigments from a number of seaweed species more effectively, including *Ulva fasciata*, *Sargassum stenophyllum*, *Pterocladiella capillacea*, and *Gracilaria opsistenuifrons* (**Amorim *et al*., 2020**). A higher yield of phycobiliprotein was obtained from distilled water extractions as opposed to those using phosphate buffer and saltwater (**Sudhakar *et al.*, 2015**). **Teramukai *et al*. (2020)** reported that fucoxanthin extraction from dried biomass was enhanced by boiling and acid/alkali treatments. Brown seaweed extraction may be more successful if edible oils like short- and medium-chain triacylglycerols are consumed. According to **Sudhakar *et al*. (2013),** boiling and freeze-drying may be more efficient methods for removing color and phytochemical components. When carotenoids were extracted from *Sargassum* spp. using nonionic surfactants such as tomadol and pluronic, more pigments were generated (**Vieira *et al.*, 2017**). **Uju *et al*. (2020)** stated that phycoerythrin and carotenoids may be extracted by ultrasonication from a range of seaweeds, including *Kappaphycus alvarezii* (phycoerythrin) and *Undaria pinnatifida* (**Zhu *et al*., 2017**). Fucoxanthin which is an unstable carotenoid has been successfully encapsulated by **Indrawati *et al.* (2015)** using Tween 80 and maltodextrin from brown seaweeds. *Porphyra* sp., *Laminaria japonica*, *Ulva* sp., *Monostroma* sp., *Hizikia fusiformis*, *Undaria pinnatifida*, *Chondrus crispus*, *Palmaria palmate*, *Caulerpa lentillifera*, *Alaria esculenta* as well as *Callophyllis variegate* and Gracilaria sp., are seaweeds that can be consumed raw as vegetables **(Gomez-Zavaglia *et al*., 2019)**. There are several uses for the abundant iron, magnesium, zinc, iodine, and carotenoids in these seaweeds in agriculture, health, and the environment. Due to their high concentration of phycobiliproteins, minerals, vitamins, agar, carotenoids, and carrageenin, red seaweeds provide health advantages (**Kolanjinathan *et al.*, 2014; Cotas *et al.*, 2020**). Sushi dishes from Southeast Asian countries often include nori, a popular edible red seaweed product, as a seasoning.

6. Fucoxanthin and phlorotannins, novel compounds made from brown seaweeds

6.1. Fucoxanthin

Brown seaweeds contain a pigment called fucoxanthin, which may be used as a dietary supplement to prevent Alzheimer's disease (**Maoka *et al*., 2016; Zarekarizi *et al*., 2019**). Because of its peculiar structure, it can degrade or isomerize in the presence of heat, air, and light (**Zhao *et al*., 2014**). According to **Iio *et al*. (2011)** and **Lakey-Beitia *et al.* (2019)**, fucoxanthin possesses anti-angiogenic, anti-inflammatory, anti-cancer, anti-malarial, anti-obesity, anti-diabetic, and anti-senile dementia properties. The Japan Food Safety Authority, the European Food Safety Authority, and the US Food and Drug Administration for Specified Health Uses have all authorized it as a safe food additive (**Shannon and Abu-Ghannam 2017**). However, because of its instability and high manufacturing costs, it is underutilized in the food and pharmaceutical industries (**D'Orazio *et al*., 2012**).

Fucoxanthin is extracted and purified using a variety of techniques, but these approaches have limitations, including low yield, low efficiency, and high solvent consumption **(Shang *et al*., 2011; Xiao *et al*., 2012; Billakanti *et al*., 2013; Kim *et al*., 2014; Kanda *et al*., 2014)**. Moreover, chromatographic methods like centrifugal partition chromatography **(Kim *et al*., 2011).**

High-purity fucoxanthin is typically obtained by column chromatography (**Sudhakar *et al*., 2013**), thin-layer chromatography (**Piovan *et al*., 2014**), and high-speed countercurrent chromatography (**Xiao *et al*., 2012**). Fucoxanthin must thus be commercialized, and its economic worth increased through the focus on developing efficient and environmentally friendly extraction and purification techniques. (**Lourenco-Lopes *et al.*, 2020**).

6.2. Phlorotannins

Brown algae include a class of polymers called phenologlucinols, which are a subclass of phenols. Fucols, fuhalols, phenols, fucophloroethols, and eckols are some of the classes into which these metabolites are categorized. Phlorotannins have a variety of physiological functions, including bioadhesion, wound healing, protection against heavy metal ion chelating, and herbivores, as stated by **Cruces *et al*. (2017).**

The bioactive characteristics of phlorotannins include protection against UV radiation, a reduction in inflammation, an increase in hair growth, and the prevention of cancer. They are employed in the pharmaceutical, cosmetic, and food industries **(Dominguez, 2013).** According to **Perez *et al.* (2016),** phlorotannins also function as biostimulants, promoting plant development and protection (**Rengasamy *et al*., 2016**). In the middle of the 20th century, brown algal extracts with phlorotannins were produced on a commercial scale as natural fertilizers (**Kim and Chojnacka, 2015**). Commercial extracts from various brown algae are recognized as plant biostimulants and are being used worldwide for a variety of agricultural crops (**Craigie, 2011**). In 2013, Martinez and Castaneda conducted a study of the chromatographic analysis, production, and structural variation of phlorotannins. 2020 saw a study of the extraction, purification, and use of phenolic chemicals from seaweeds (**Cotas *et al*., 2020**).

Phenolitannins from brown algae can be extracted using a variety of techniques, including ultrasonic sound aided extraction, enzyme-assisted extraction, pressured liquid extraction, surfactant-mediated extraction, microwave-assisted extraction, and so on. (**Yilmaz and colleagues, 2019**). Moreover, a range of methods are used to generate phlorotannin-containing fractions, including liquid biphasic systems, centrifugal partition chromatography, and high-speed counter-current chromatography, which are frequently employed (**Lee *et al*., 2014**; **Chia *et al.*, 2018; Zhou *et al*., 2019**) and macroporous resin chromatography (**Leyton *et al*., 2017)**.

Phlorotannin-containing extracts are utilized in agriculture, whereas fractionated phlorotannins are used as high-value products as ingredients in foods, medications, and cosmeceuticals **(Chojnacka *et al*., 2018).** Moreover, phlorotannins have antioxidant properties and are used as natural nutraceuticals to prevent diabetes by inhibiting human salivary alpha-amylase **(Gisbert *et al*., 2023).**

Conclusion

Seaweeds, rich in bioactive chemicals like assaponins, flavonoids, polyphenols, and lectins, can have anti-nutritional effects if consumed in large quantities. However, improper dosages can also have health effects. Seaweeds thrive in high-pressure zones and high salinity concentrations, making them a valuable protein source and a sustainable source of amino acids as well as essential vitamins and phytochemicals. They can contribute to the UN's goal of eliminating hunger by 2030. Seaweeds are used in various food products, including supplements, salads, pasta, bread, and weight management. They also serve as dietary additives, antioxidant agents, and microbiological agents in agar production. They are also used in egg substitutes and meatless burgers and patties. Despite their potential, more research is needed to fully understand their potential.

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