Review Article

Seaweed as a Source of Natural Antioxidants: Therapeutic Activity and Food Applications

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Seaweed is a valuable source of bioactive compounds, polysaccharides, antioxidants, minerals, and essential nutrients such as fatty acids, amino acids, and vitamins that could be used as a functional ingredient. The variation in the composition of biologically active compounds in seaweeds depends on the environmental growth factors that make seaweed of the same species compositionally different across the globe. Nevertheless, all seaweeds exhibit extraordinary antioxidant potential which can be harnessed for a broad variety of food applications such as in preparation of soups, pasta, salads, noodles, and other country specific dishes. This review highlights the nutritional and bioactive compounds occurring in different classes of seaweeds while focusing on their therapeutic activities including but not limited to blood cell aggregation, antiviral, antitumor, anti-inflammatory, and anticancer properties. The review also explores the existing and potential application of seaweeds as a source of natural antioxidant in food products. Seaweed-derived compounds have great potential for being used as a supplement in functional foods due to their high stability as well as consumer demand for antioxidant-rich foods.

1. Introduction

“Good food, good health,” this phrase means a lot itself. Nowadays, people bear a lot of stress in their life due to their burdened schedule. The intense stress leads to the generation of free radicals in the body that facilitates rapid ageing. To eliminate stress, one can perform meditation, eat healthy food, do yoga and exercise, etc. Out of these, the most important source to eradicate stress is to eat healthy food, enriched in antioxidants, minerals, vitamins, proteins, fibres, etc. It has been seen that processed food contains synthetic preservatives which oxidize functional component in the food causing oxidative stress, hypertension, and cardiovascular diseases, among others. To replace the synthetic preservatives or additives in processed foods, natural bioactive compounds may be extracted from natural

commodities that can be added to processed foods to neutralize oxidation. Macroalga or seaweed is one such natural commodity that is enriched in antioxidants, polyphenols, protein, minerals, and vitamins and possesses various therapeutic activities such as antibacterial, antiviral, anticancer, and antioxidant properties [1]. Therefore, seaweed is a more preferable source of bioactive compounds as it has more stable antioxidants as compared to terrestrial plants [2] and helps in preventing oxidative stress and other mammalian diseases.

Seaweeds are primary plants that do not bear flowers, roots, stems, and leaves [3]. They are found at the bottom of the sea up to 180 m and are mostly found in solid substrates onto a depth of 30–40 m. They grow in estuaries and are attached to rocks, shells, stones, and other plant materials [3].

From ancient times, seaweeds have been utilized as medicine for many years in Japan (13,000–300 BC), China (2,700 BC), Egypt (1,550 BC), and India (300 BC) [4].

Production of seaweeds is done utilizing two sources: the wild (natural marine system) and aquaculture (controlled system). Considering all seaweeds, the wild type accounts for about 4.5% of the production while cultivated seaweed production has grown by about 50% in the last decade [5, 6]. According to FAO [7] statistics, for the last 10 years (2003 to 2012), the production of seaweeds from wild stocks was found stable and in 2012, the top producers were Chile (436,035 tons) followed by China (257,640 tons) and Japan (98,514 tons). The Indian annual production was 1 ton for the last ten years. It was also highlighted in the FAO report that the production of seaweeds from aquaculture (24.9 million tons) was more than the wild (1 million ton) with major producers and cultivators being China and Japan.

Three groups of seaweeds are classified based on pigments, viz., brown (Ochrophyta, Phaeophyceae), green (Chlorophyta), and red (Rhodophyta) seaweeds containing fucoxanthin, chlorophyll a, chlorophyll b, phycocyanin, and phycoerythrin, respectively [4]. The red seaweeds are most abundantly present with more than 7000 species, followed by brown and green seaweeds with 2030 and 600 species, respectively [3]. Brown seaweeds contain a wide range of sizes from giant kelp of over 20 m long to small size seaweeds of 30–60 cm long. Red seaweeds are generally small in size varying from a few centimeters to about a meter long, and green seaweeds have a similar range size as red seaweeds [7].

In ancient times, seaweed was used as medicine as it provided health benefits. It is a valuable source of bioactive compounds, phytochemicals, polysaccharides, fibre, ω -3 fatty acids, and essential amino acids with almost all vitamins and minerals such as calcium, potassium, sodium, and phosphorus [8]. Therefore, seaweeds are claimed to have commercial applications in the nutraceutical, agricultural, food, medical, pharmaceutical, and cosmetic industries [4]. Due to good source of nutrients, seaweeds are used as human food in different countries. Around 42 countries in the world commercially utilize seaweeds. Among them, China holds the first rank, followed by North Korea, South Korea, Japan, Philippines, Chile, Norway, Indonesia, USA, and India [9].

The rich biochemical composition and novel bioactive compounds of seaweeds are due to their ability to survive in a complex environment that generates tremendous quantities of secondary metabolites that is not generated in terrestrial plants and is unparalleled [2]. These characteristics increased the interest among the scientific community to use seaweed as a functional ingredient for diverse industrial applications. Functional substances in marine algae such as lectin, acrylic acid, polysaccharides, fucoidan, alginic acid, and agar, extracted from *Gracilariopsis longissima* (formerly *Gracilaria verrucosa*), *Ulva intestinalis* (formerly *Enteromorpha intestinalis*), *Saccharina latissima* (formerly *Laminaria saccharina*), *Eisenia bicyclis*, and *Undaria pinnatifida*, function as blood cell aggregators and exhibit antibiotic, antitumor, antiarteriosclerosis, and anticancer properties, respectively [10]. The antioxidant activity of

seaweeds is due to carotenoids, polysaccharides, vitamins, and its precursor and polyphenols, which contribute to the inhibition of oxidation processes [11]. Seaweeds are also used as a supplement in traditional foods and for the extraction or isolation of bioactive compounds for the development of nutraceutical supplements. Since there is an increasing demand of nutrient-rich food, this review discussed the possible use of seaweeds as a natural source of bioactive compounds and antioxidant. The utilization of seaweeds as a functional ingredient in various food matrix to develop diverse biological activities, such as antimicrobial, anti-inflammatory, anticoagulant, anticancer, and anti-hypertension activity, has also been discussed.

2. Classification of Macroalgae

Different species of macroalgae are found in different coastlines of the world which are classified into three taxonomic groups based on pigments as shown in Table 1 [12, 13].

2.1. Brown Seaweed (Phaeophyceae). The color of brown seaweeds is due to the presence of the xanthophyll pigment, fucoxanthin [14]. Brown seaweeds are large and measure about 2 to 65 m long and thick and leather-like, and their smaller species is about 30–60 cm long [7, 13]. Some Indian brown seaweeds are *Dictyota ceylanica* [15] and *Sargassum wightii* [16]. Japanese brown seaweeds include *Laminaria* sp., *Saccharina* sp., *Undaria* sp., *Nemacystus* sp., *Sargassum* sp. (formerly *Hizikia* sp.), *Eisenia* sp., and *Ecklonia* sp. [17].

2.2. Red Seaweed (Rhodophyta). The color of red seaweeds is due to phycocyanin, phycoerythrin, chlorophyll a, and xanthophyll pigments [3]. They are small in size, ranging from few centimeters to about a meter long [7]. Some Indian red seaweeds are *Catenella caespitosa* (formerly *Catenella repens*), *Polysiphonia mollis*, and *Gelidiella acerosa* [15] and some Japanese red seaweeds are *Porphyra* sp., *Gelidium* sp., and *Gracilaria* sp. [17].

2.3. Green Seaweed (Chlorophyta). The color of green seaweeds is yellow to green due to the presence of beta-carotene, chlorophyll a and chlorophyll b, and xanthophylls [14]. They are small in size similar to red seaweeds [7]. Some Indian green seaweeds are *Rhizoclonium riparium*, *Ulva intestinalis* (formerly *Enteromorpha intestinalis*), *Chaetomorpha ligustica* (formerly *Lola capillaris*), and *Ulva lactuca* [15] while *Monostroma* sp. is a Japanese green seaweed [17].

3. Composition and Nutritive Profile of Seaweeds

Different species of seaweeds in different locations of the world exhibit different compositional profile. Here we discuss a case study of Indian coastal seaweeds. In the Mandapam coastal regions of the southeast coast of India, *Padina gymnospora*, *Ulva lactuca*, *Ulva intestinalis* (formerly *Enteromorpha intestinalis*), *Gracilaria foliifera*, *Sargassum*

TABLE 1: The general classification of macroalgae (after [12, 13]).

Domain	Kingdom	Phylum	Class
Prokaryota	Eubacteria	Cyanobacteria	Cyanophyceae
	Plantae	Rhodophyta	Bangiophyceae Florideophyceae
Eukaryota	Chromista	Ochrophyta	Phaeophyceae Bryopsidophyceae
	Plantae	Chlorophyta	Siphonocladophyceae
			Ulvophyceae

tenerrimum, *Codium tomentosum*, and *Hypnea valentiae* can be found [18]. In the Tuticorin coast of Southeast India, *Turbinaria ornata* and *Gracilariopsis longissima* (formerly *Gracilaria verrucosa*) can be found [19]. From the coastal regions of Chilika Lake of India is *Ulva rigida* [20]; from the sea coast of Rameshwaram, Tamil Nadu, India, is *Kappaphycus alvarezii* [21]; from the east coast of India are *Caulerpa racemosa*, *Ulva lactuca* (formerly *Ulva fasciata*), *Chnoospora minima*, *Padina gymnospora*, and *Acanthophora spicifera* [22]. Even within the same country, the seaweed composition in different coast varies due to different microenvironments. Table 2 shows the basic composition of different seaweed classes.

3.1. Protein and Amino Acids. According to the above species of seaweeds, the protein content ranges from 1.8 to 18.9%. The maximum protein content was recorded in Phaeophyceae members and a minimum in Chlorophyta members [31]. A total of 16 amino acids have been reported in seaweeds (*Caulerpa racemosa*, *Ulva lactuca* (formerly *Ulva fasciata*), *Chnoospora minima*, *Padina gymnospora*, and *Acanthophora spicifera*) collected from the east coast of India. *Acanthophora spicifera* contain the highest concentration of glutamic acid and aspartic acid of 17.4% and 15.7%, respectively [22]. Protein content variation among different species of seaweed is due to the surrounding water quality as reported by Dhargalkar et al. [32].

3.2. Lipid and Fatty Acids. The lipid content ranges from 1.5 to 5%. Lipid content is maximum in Chlorophyta members and minimum in Rhodophyta members [31]. Seaweeds are rich in essential fatty acids. For instance, green seaweeds have the maximum content of α -linolenic acid (C18:3n-3) while the red and brown seaweeds are rich in 20 carbon atoms: eicosapentaenoic acid (EPA, C20:5n-3), C18:4n-3 (octadecatetraenoic), C20:4n-6 (arachidonic acid), C20:5n-3 (DPA), and C22:6n-3 (DHA) [8, 33]. The brown algae *Dictyota ceylanica* contains 24.4% palmitic acid, 15.6% stearidonic acid, 15.4% oleic acid, 11.2% linolenic acid, 8.2% eicosapentaenoic acid, and 7.5% arachidonic acid [15]. Seaweed is a good source of omega 3 and omega 6 fatty acids which help to prevent many diseases such as cardiovascular diseases, arthritis, and diabetes [33].

3.3. Carbohydrates and Dietary Fibre. The carbohydrate content ranged from 12 to 65%. Carbohydrate content is maximum in Chlorophyceae members followed by

Rhodophyceae and Phaeophyceae members [31]. The total dietary fibre (TDF) content of *Hydropuntia edulis* (formerly *Gracilaria edulis*) (red seaweed), *Ulva lactuca* (green seaweed), and *Sargassum* sp. (brown seaweed) ranges between 53.625 ± 0.18 and $63.175 \pm 0.46\%$ on a dry weight basis [34]. There is a need to evaluate the total dietary fibre of different species of seaweed as very less work has been reported for dietary fibre estimation in recent studies.

3.4. Minerals. According to Bergner [35], seaweeds are a rich source of minerals compared to terrestrial plants and have more bioavailability. Seaweeds provide almost all essential minerals [36], with a composition of 7–38% minerals of their dry weight. The elements found in seaweeds are potassium, sodium, fluorine, calcium, iron, magnesium, arsenic, zinc, copper, iodine, chloride, bromine, sulphur, selenium, phosphorous, manganese, vanadium, and cobalt. The brown seaweeds (*Sargassum* sp., *Laminaria* sp., and *Undaria* sp.) contain higher amount of minerals than red seaweeds (*Porphyra* sp. and *Eucheuma* sp.) [36]. *Padina tenuis* and *Sargassum odontocarpum* (formerly *Sargassum coriifolium*) contain a higher amount of macrominerals with iron in lesser amounts [31].

3.5. Vitamins. Generally, seaweeds are rich in water-soluble vitamins and commonly contain vitamins A, B₁₂, C, β -carotene, pantothenate, folate, riboflavin, and niacin. Seaweeds also contain higher amounts of vitamins than fruits and vegetables. The class Phaeophyceae is rich in water-soluble vitamins such as vitamins B₁ (thiamine), B₂ (riboflavin), B₆, and nicotinic acid [31]. Therefore, seaweeds have the potential to solve the problem of iodine and other mineral and vitamins deficiency [31]. These biological activities of seaweeds play an important role in the development of functional food which prevents many harmful diseases.

4. Bioactive Compounds in Seaweeds

4.1. Agar. Agar is a polysaccharide extracted from the red seaweeds (*Gracilaria* sp. and *Gelidium* sp.). It is a mixture of agarose and agarpectin where agarose [37] (Figure 1) is a linear chain of polymer consisting of 1,4-linked α -3,6-anhydro-L-galactose and 1,3-linked β -D-galactose repeating units and agarpectin is a sulphated polysaccharide composed of agarose and other components such as D-glucuronic acid, ester sulphate, and a small amount of pyruvic

TABLE 2: Composition on % dry weight basis of different seaweeds.

Seaweed	Protein	Fat	Carbohydrate	Crude fibre
Brown seaweed				
<i>Sargassum wightii</i> ^c	1.482 mg/g	0.0272 g/g	0.095 mg/g	17%
<i>Padina gymnospora</i>	17.08 ^e	11.4 ^j	21.88 ^e	—
<i>Sargassum tenerrimum</i> ^e	12.42	1.5	23.55	—
<i>Turbinaria ornata</i> ^f	14.68	3.1	12.5	—
<i>Sargassum odontocarpum</i> (formerly <i>Sargassum coriifolium</i>) ⁱ	16.07	0.5	47.43	6.5
<i>Padina boryana</i> (formerly <i>Padina tenuis</i>) ⁱ	8.32	0.5	41.68	2.5
<i>Chnoospora minima</i> ^j	11.3	0.9	28.5	—
<i>Cystoseira compressa</i> ⁿ	89.1 g/kg	18.3 g/kg	396.2 g/kg	—
<i>Ericaria amentacea</i> (formerly <i>Cystoseira stricta</i>) ⁿ	141.4 g/kg	27.1 g/kg	354.5 g/kg	—
Red seaweed				
<i>Crassiphycus changii</i> (formerly <i>Gracilaria changii</i>) ^b	12.57	0.30	41.52	64.74
<i>Gelidiella acerosa</i> ^a	9.18	3.83	14.34	—
<i>Hydropuntia edulis</i> (formerly <i>Gracilaria edulis</i>) ^l	6.68 mg/g	8.3 mg/g	101.61 mg/g	8.9%
<i>Gracilariopsis longissima</i> (formerly <i>Gracilaria verrucosa</i>) ^f	9.47	3.1	15.0	—
<i>Gracilaria foliifera</i> ^e	6.98	3.23	22.32	—
<i>Hypnea valentiae</i> ^e	8.34	1.5	23.60	—
<i>Kappaphycus alvarezii</i> ^h	18.78	1.09	2.67	—
<i>Acanthophora spicifera</i> ^j	18.9	2.1	65	—
<i>Ellisolandia elongata</i> (formerly <i>Corallina elongata</i>) ⁿ	58.5 g/kg	6.4 g/kg	134.0 g/kg	—
Green seaweed				
<i>Ulva lactuca</i> ^a	8.44	4.36	35.27	60.5 ^k
<i>Ulva compressa</i> (formerly <i>Enteromorpha compressa</i>) ^d	12.27	0.81	17.0	29 ^m
<i>Ulva intestinalis</i> (formerly <i>Enteromorpha intestinalis</i>)	16.38 ^e	7.13 ^a	28.58 ^f	—
<i>Ulva clathrata</i> (formerly <i>Enteromorpha clathrata</i>) ^e	11.5	4.6	24.5	—
<i>Codium tomentosum</i> ^e	6.13	2.53	20.47	—
<i>Ulva rigida</i> ^g	6.64	12.0	22.0	38–40 ^m
<i>Ulva lactuca</i> (formerly <i>Ulva fasciata</i>) ^j	14.7	0.5	70.1	—
<i>Caulerpa racemosa</i> ^j	18.3	19.1	83.2	64.9 ^m

^aChakraborty et al. [15]; ^bChan et al. [23]; ^cSyad et al. [24]; ^dManivannan et al. [25]; ^eManivannan et al. [18]; ^fParthibhan et al. [19]; ^gSatpati et al. [20]; ^hRajasulochana et al. [21]; ⁱHaque et al. [26]; ^jAfonso et al. [27] ^kOrtiz et al. [28]; ^lSaktivel et al. [29]; ^mPereira et al. [30]; ⁿOucif et al. [8].

FIGURE 1: Structure of agar polysaccharides.

acid [38]. Agar-Agar has an important biological activity as it acts as an antitumor agent, reduces oxidative stress, and reduces the level of blood glucose in the human body. Other applications are used as cell culture medium and manufacture of capsules [37]. It has various applications in the food industries including its use as a texture improver in dairy products like cheese, cream, and yogurt and use as a stabilizer in the processing of ices and sherbets. In alcoholic industries, it is used as a clarifying agent for wines, especially plum wines [39].

4.2. Carrageenan. Carrageenan is a linear chain polysaccharide, extracted from red seaweed, *Chondrus crispus*, and *Kappaphycus* sp. that contains up to 71% and 88% of

carrageenan, respectively. Polysaccharide chains consist of sulphate half-esters that are attached to the sugar unit. Carrageenan has three forms, viz., kappa, lambda, and iota, each with its own gelling property [37] (Figure 2). Kappa carrageenan is 4-sulfated on the 3-linked residue and has a 3,6-anhydro bridge on the 4-linked residue while lambda carrageenan has 2,6-disulfated 3-linked residue and 70% sulfation at position 2 of the 4-linked residues. Kappa carrageenan is potassium-sensitive and may be precipitated from dispersions by potassium, while lambda carrageenan is not sensitive to potassium [38]. Carrageenan has many food applications such as in canned food products, dessert mousses, salad dressings, and bakery fillings, as stabilizer in ice cream and instant dessert preparations, in canned pet foods, and in clarifying beer, wines, and honey [37].

FIGURE 2: Structure of (a) kappa carrageenan, (b) iota-carrageenan, and (c) lambda carrageenan.

4.3. Algin. Stanford discovered the algin in 1881 where it found that sodium carbonate treated with Laminariaceae macroalgae produces the viscous solution known as alginic acid. Alginic acid is a polysaccharide composed of β -D-mannuronic acid and α -L-guluronic acid residues joined by β -1,4-linkage [38]. In pyranose conformation, two uronic acid residues offer three different sequences after partial acid hydrolysis [40]. Algins are also called alginates and can be extracted from brown seaweeds which make up 10% to 30% algin of their dry weight [38]. Alginates are commercially extracted from seaweeds such as *Durvillaea antarctica*, *Ascophyllum nodosum*, *Macrocystis pyrifera*, *Lessonia nigrescens*, *Sargassum turbinaroides*, and *Ecklonia maxima* [40]. Alginates are used in the stabilization of ice-lollies and the manufacture of sausages, thickening agents, and gel-forming agents, in the food industry [40, 41]. Alginates are polyelectrolytes that selectively bind the alkaline Earth metals such as calcium and sodium ions that help in gel formation [40].

4.4. Mannitol. D-mannitol is an acyclic hexanol (first sugar alcohol) [42] which was extracted from brown seaweed in 1884 by Stenhouse [38]. Brown seaweed is composed of mannitol up to 20–30% of the dry weight and its level varies in green and red seaweeds [42]. Many functional activities are imparted for mannitol such as carbohydrate storage, translocatable assimilate, source of reducing power, osmoregulation, and scavenging of active oxygen species [43]. Mannitol can be extracted from seaweeds such as *Laminaria*

sp., *Sargassum pacificum* (formerly *Sargassum mangar-evense*), and *Turbinaria ornata* [44].

4.5. Iodine. It was reported that many Indian and Japanese seaweeds contain iodine content which is present in low molecular weight iodate form (83%–86%) and easily absorbed in the human alimentary tract. The Japanese seaweeds like *Saccharina japonica* (formerly *Laminaria japonica*), *Ecklonia* sp., *Sargassum fusiforme* (formerly *Hizikia fusiformis*), and *Undaria pinnatifida* consist of 145, 315, 60, and 5.7 mg/100 g dry matter of iodine content, respectively. It was also reported that green and red seaweeds have more iodine content than brown seaweeds [38]. Iodine is essential for thyroid hormone synthesis and imparts antioxidant and antiproliferative activity in the prevention of cancer and cardiovascular diseases [45].

4.6. Fucoidan. In 1915, Kylin named the term fucoidan, which is extracted from brown seaweed with dilute acid (0.01 N HCl). It is a polymer of fucan sulphate with units of 1,2-linked L-fucose-4-sulfate (Figure 3) and in some cases, it additionally contains 1,3- or 1,4-linked fucan sulphate which carries side chain of galactose, xylose, and uronic residues [38]. Fucoidans are extracted from brown seaweeds such as *Ecklonia cava*, *Saccharina longicuris*, *Fucus vesiculosus*, *Ascophyllum nodosum*, and *Undaria pinnatifida* [46, 47]. Fucoidan is a sulphated polysaccharide containing important biological activities due to having a different amount of sulphate group in its chemical structure. It has

FIGURE 3: Chemical structure of fucoidan.

anticoagulant, immunomodulation, anticancer, antiviral, anticomplement, antithrombotic, and antiproliferative activity [48].

4.7. Laminaran. Laminaran is a storage polysaccharide (β -glucan) that consists of 20 glucose residues joined by β -1,3-linkage. There are two types of laminaran, viz., a “soluble laminaran” and an “insoluble laminaran” obtained from *Laminaria hyperborea* (formerly *Laminaria cloustonii*) and *L. digitata*, respectively; the latter is soluble in hot water. Based on the amount of mannitol present in both laminarans, two chains, M- and G-chains, are produced (Figure 4) where mannitol residues occupy the reducing terminal region in M-chains and glucose residues occupy the terminal region in G-chains [38]. The biological activity of laminaran includes antitumor activity, antiapoptosis activity, and immunomodulatory effects [49].

4.8. Phlorotannin. Phlorotannins are a class of tannins synthesized in brown seaweeds and derived from phloroglucinol (1,3,5-trihydroxybenzene) monomer units. Phloroglucinol is a polyphenol consisting of aromatic phenyl ring with 3-OH groups that accumulate in brown seaweeds [50]. It is biosynthesized by the acetate-malonate or polyketide pathway. Due to wide range of molecular sizes, it has been grouped according to interphloroglucinol linkages into four types such as phlorethols (with only aryl ether bonds), eckols (with dibenzodioxin linkages), fucols (with only phenyl linkages), and fucophloroethols (with phenyl and aryl ether linkages) [51]. Various phlorotannin compounds like bieckol/dieckol, fucophloroethol, phlorofucofuroeckol, fucodiphloroethol, 7-phloroeckol, and fucotriphloroethol have been reported in different brown seaweeds such as *Gongolaria usneoides* (formerly *Cystoseira usneoides*), *Pelvetia canaliculata*, *Ascophyllum nodosum*, *Fucus spiralis*, *Gongolaria nudicaulis* (formerly *Cystoseira nudicaulis*), *Fucus vesiculosus*, *Saccharina longicuris*, and *Ericaria selaginoides* (formerly *Cystoseira tamariscifolia*) [52, 53]. Phlorotannin has eight interconnected rings in its structure which make it a potent free radical scavenger compared to the terrestrial plants [50]. Therefore, this phenomenon shows a variety of therapeutic activities of phlorotannin such as antimicrobial, antioxidant, anti-inflammatory, antidiabetic, anti-HIV, and antiallergic [54]. However, further studies are being carried out for the development of nutraceutical from phloroglucinol.

4.9. Carotenoids. Carotenoids are tetraterpenoids that are used for the classification of seaweeds (red, green, and brown) [55]. Based on metabolism and function, they are divided into two groups, primary and secondary carotenoids. Primary carotenoids are the structural and functional components that help in photosynthesis. Secondary carotenoids are the extraphotosynthetic pigments which are produced through carotenogenesis under specific environmental conditions. Primary carotenoids include α -carotene, β -carotene, violaxanthin, neoxanthin, fucoxanthin, zeaxanthin, and lutein, whereas secondary carotenoids include astaxanthin, canthaxanthin, and echinenone [56]. Carotene is a primary precursor of vitamin A, which prevents night blindness and cataract and helps in the formation of glycoprotein, secretion of mucus from epithelial tissues, cell differentiation, overall development of body and bones, and reproduction. Carotenoids have many functional activities such as antioxidant activity and immune boosting activity and reduce the risk of chronic diseases such as cardiovascular diseases, inflammation, age-related muscular diseases, cancer, obesity, and neurological diseases [56, 57]. Seaweeds that contain primary carotenoids include *Fucus* sp., *Undaria pinnatifida*, *Sargassum* sp., *Sargassum fusiforme* (formerly *Hizikia fusiformis*), and *Saccharina japonica* (formerly *Laminaria japonica*) [56].

4.10. Fucoxanthin. Fucoxanthin is a carotenoid-xanthophyll containing two functional groups, oxygenic and carboxyl groups, linked by allenic bond in the polyene hydrocarbon chain which provides high antioxidant activity [54]. Also, it binds with chlorophyll and proteins to form a stable fucoxanthin-chlorophyll-protein complex that distinguishes it from other plant carotenoids [1]. Fucoxanthin contains more antioxidant activity than other carotenoid pigments due to the presence of conjugated double bonds with epoxide and acetyl substituent groups attached to a polyene [1], whereas carotenoid synthesis in algae may highly depend on the environmental factors, temperature, salinity, irradiance, nutrient concentration, etc. In brown seaweeds, the common species from which fucoxanthin is extracted are *Undaria pinnatifida*, *Sargassum fusiforme*, *Sargassum fulvellum*, *Saccharina japonica*, *Padina tetrastrum*, *Sargassum siliquastrum*, *Turbinaria turbinata*, and *Sargassum plagiophyllum* [58]. The fucoxanthin-chlorophyll-protein complex might be the reason for the therapeutic activity of fucoxanthin such as antioxidant, anti-inflammatory, anticancer, antiobesity, and antidiabetic activity [54]. The major

FIGURE 4: Chemical structures of one unit of (a) M-chain and (b) G-chain of laminaran.

isomer of fucoxanthin found is transfucoxanthin (Figure 5) which exhibits apoptosis in cancer cells (prostate cancer- (PC-) 3, LNCap cells, DU 145, and leukemia HL-60 cells) and regulates cell cycle arrest during G0/G1 stage neuroblastoma GOTO cells [58].

4.11. Ulvan. Ulvan is a sulphated polysaccharide, extracted from green seaweed (*Ulva lactuca* and *Ulva rigida*). The main constituents of ulvan are sulphate (12.80–23%), uronic acids (6.50%–25.96%), rhamnose (12.73%–45%), and xylose (2%–12%) [59]. Ulvan structure contains number of oligosaccharide repeating structural units. It also contains major and minor repeating units of ulvanobiouronic acid 3-sulfate (containing either glucuronic or iduronic acid) (Figure 6) and contains sulphated xylose that replaces the glucuronic acid or uronic acid as a branch on O-2 of the rhamnose-3-sulfate, respectively [60, 61]. It has several biological activities such as an antihyperlipidemic, antiviral, antitumor, anticoagulant, and antioxidant activities. Antioxidant activity of ulvan depends upon the concentration of sulphated polysaccharides [59].

5. Therapeutic Activity of Seaweeds

5.1. Antioxidant Activity. Antioxidants are the substances that scavenge the reactive oxygen species (superoxide anion ($O_2^{\cdot-}$), hydrogen peroxide (H_2O_2), hydroxyl radical ($OH^{\cdot}$)/reactive nitrogen species (NO), and free radicals which

develop oxidative stress in the human body [62]. Due to oxidative stress, biological macromolecules such as DNA, proteins, and nucleic acid are damaged and lead to various harmful diseases such as cancer, diabetes, stroke, Alzheimer's, Parkinson's, and cardiovascular diseases [63]. Therefore, antioxidant compounds play an important role to prevent health from harmful factors. It is known that seaweeds contain several bioactive compounds with potential/higher antioxidant activity as compared to the terrestrial plants due to the presence of up to eight interconnected polyphenols rings [64]. Antioxidant activity of seaweeds is due to the presence of pigments chlorophylls, xanthophylls (fucoxanthin), carotenoids, vitamins (vitamins B1, B3, C, and E) and vitamin precursors such as α -tocopherol, β -carotene, lutein, and zeaxanthin, phenolics such as polyphenols (gentisic acid, phloroglucinol, gallic acid, protocatechuic acid), flavonoids (i.e., rutin, quercetin, myricetin, flavones, flavonols, flavanones, chalcones, hesperidin and flavan-3-ols, isoflavones, methylated flavones), lignins, tocopherols, tannins, and phenolic acids and hydroquinones, phospholipids particularly phosphatidylcholine, terpenoids, peptides, and other antioxidative substances, which directly or indirectly contribute to the inhibition or suppression of oxidation processes [65–68]. Phenolic phytochemicals act as antioxidants to stop the formation of free radical and oxidation of unsaturated lipids and low-density lipoprotein which is responsible for cardiovascular diseases [69]. Fujimoto and Kaneda [70] investigated the antioxidant activity of twenty-one species of

FIGURE 5: Chemical structure of all transfucoxanthin

FIGURE 6: Chemical structure of disaccharide units in ulva (ulvan: ulvanobiouronic acid).

marine algae out of which 60% showed the antioxygenic effect and chloroform soluble extract of brown algae showed the maximum antioxygenic effect. Anggadiredja et al. [71] reported that the antioxidant activity in methanol extract of *Sargassum polycystum* and *n*-hexane of *Laurencia obtusa* was more active than the diethyl ether.

5.2. Antimicrobial Activity. Antimicrobials are the substances that kill or inhibit the growth of microorganisms while antibiotics and antifungals are the medicines which help to kill bacteria and fungus, respectively. Antimicrobial substances generally affect the microbial cells, attacking the cell membrane's phospholipid bilayer, degrading the enzyme systems, and disrupting the genetic material of the microorganisms [72]. Secondary metabolites from seaweeds such as polyphenols can disrupt the microbial cell permeability, interfere with membrane function/cellular integrity, and cause cell death [73]. Sieburth detected the first antibiotic compound acrylic acid, formed from dimethylpropiothetin in the microalga *Phaeocystis pouchetii* (class Coccolithophyceae). Acrylic acid is isolated from *Ulva* (formerly *Enteromorpha*) and *Ulva australis* (formerly *Ulva pertusa*) which is responsible for antibacterial action [38]. Sodium alginate from red seaweeds showed antibacterial action against *E. coli* and *Staphylococcus* [37]. Halogenated aliphatic compounds (halogenated heptanones, haloacetones, and halobutanone) occurring in genera *Asparagopsis* and *Bonnemaisonia* (Rhodophyta) showed antibiotic activity against *Bacillus subtilis*, *Staphylococcus*, *Fusarium*, and *Vibrio* [38]. Rajauria et al. [74] suggested that the algal polyphenols such as tannins, quinones, flavones, flavonols, phlorotannins, and flavonoids are responsible for the antimicrobial activity. Methanolic extracts of *Himanthalia elongata* showed antibacterial activity against food spoilage (*E. faecalis* and *P. aeruginosa*) and pathogenic bacteria (*L. monocytogenes* and *S. abony*) [74]. Terpenes, phlorotannins (isolated from *Ecklonia cava* subsp. *kurome*

formerly *E. kurome*, *Ecklonia cava*, and *Fucus vesiculosus*), and lipophilic compounds have shown antimicrobial action against Gram-positive and Gram-negative bacteria [75]. Along with polyphenols, algal polysaccharides also represent antimicrobial activity by recognizing and binding on glycoprotein receptors of bacterial surface which is attributed to disrupting the bacterial cell [72].

5.3. Anti-Inflammatory Activity. Anti-inflammatory substances are those which reduce inflammation or swelling. Inflammation occurs due to the movement of increasing leucocytes from blood to tissues [76] and causes dysfunction and various diseases such as carcinogenesis, rheumatoid arthritis, Crohn's disease, osteoarthritis, ulcerative colitis, and sepsis [77]. Macrophages release inflammatory factors, viz., nitric oxide (NO), inducible nitric oxide synthase (iNOS) tumor necrosis factor- α , interleukin-1 β , and prostaglandin E2. Lipopolysaccharides (LPS) trigger inflammation in macrophages and induce the production of proinflammatory cytokines by activating a set of intracellular signalling cascades [78]. The first example of diphenyl ether extract from green seaweed *Cladophora vagabunda* (formerly *Cladophora fascicularis*) was isolated to develop an anti-inflammatory compound, 2-(20,40-dibromophenoxy)-4,6-dibromoanisole. This compound helps to prevent the growth of bacteria such as *Bacillus subtilis*, *Escherichia coli*, and *Staphylococcus aureus* [79]. Other anti-inflammatory compounds include macrolides, lipophorins A 142 and B 143, and bromophenol metabolites named vidalols A and B which have been isolated from the surface of the brown alga *Lobophora variegata* [80] and red algae *Osmundaria obtusiloba* (formerly *Vidalia obtusiloba*), respectively, and compound vidalols A and B that act through the inhibition of phospholipase enzyme [81]. Alginate also showed an anti-inflammatory effect, and it has no adverse effect on human health [37]. Along with this seaweed, sulphated polysaccharides from the brown seaweeds (*Sargassum wightii* and

Halophila ovalis) and the red seaweeds (*Crassiphycus corneus* (formerly *Gracilaria cornea*) and *Caulerpa racemosa*) showed anti-inflammatory activities [78].

5.4. Antiviral Activity. Antiviral compounds are the substances that inhibit the replication cycle of a virus at a certain stage without causing any toxicity to the body cells. Poly-anionic substances are the antivirals that help in inhibiting the replication of viruses. According to the anion present, antivirals are divided into four types, polysulphates, polyoxometalates, polycarboxylates, and polysulfonates. Amongst them, polysulphates are the most valuable class that includes sulphated polysaccharides and sulphated derivatives of polystyrenes, polyvinyl alcohols, naphthalenes, and polyacetals. Sulphated polysaccharides from seaweeds such as alginates, carrageenans, agarans, DL-hybrid galactans, laminarans, fucans, and fucoidans are described as inhibitors of the replication of various enveloped viruses, as human cytomegalovirus, human immunodeficiency virus, respiratory syncytial virus, dengue virus, influenza A and B virus, junin, tacaribe virus, simian immunodeficiency virus, and herpes simplex virus [82–84]. Seaweeds can therefore be an effective source to combat the symptoms of SARS-CoV-2 virus (coronavirus). Polysulphates contain negative charge due to the presence of sulphate residues and interact with positively charged viral glycoproteins that provide cell contact. Generally, it was known that the antiviral activity of sulphated polysaccharides increases with an increase of molecular weight and degree of sulfation. Therefore, the entry of viruses to host cells is restricted due to this complex process involving the binding of the virion envelope with the polyanionic substances [83]. The antiviral compounds isolated from different seaweeds have been presented in Table 3.

5.5. Antilipidemic and Hypocholesterolaemic Activity. The rise of cholesterol level and blood pressure causes cardiovascular diseases in the human body. Bioactive compounds present in seaweeds could prevent hyperlipidemic and hypercholesterolemic effects. The hypocholesterolemic and hypolipidemic response is produced by increasing faecal cholesterol content and by lowering of systolic blood pressure, respectively [110]. Alginates, a sulphated polysaccharide (molecular weight ≥ 50 kDa), and alginic acid produced from *Laminaria* sp. could prevent the onset of diabetes, hypocholesterolemia, and obesity [111]. Dietary fibres of seaweeds absorb substances like cholesterol and eliminate them from the digestive system, resulting in hypocholesterolemic and hypolipidemic response [37]. Ethanolic extracts of *Caulerpa racemosa*, *Colpomenia sinuosa*, *Spatoglossum asperum*, *Iyengaria stellata*, and *Solieria robusta* are responsible for hypolipidemic activities [110].

5.6. Antithrombotic and Anticoagulant Activity. Alginate, a sulphated polysaccharide, has prothrombotic blood coagulation and platelet activation activity [37]. Fucan, a sulphated polysaccharide extracted from *Fucus vesiculosus*, possesses the same activity as heparin that suppresses blood

coagulation in humans. As compared to heparin, fucan mostly retards the activity of thrombin on fibrinogen [38]. Fucans consist of homo- and heterostructure. Homofucans have α -(1 $\rightarrow$ 3) and α -(1 $\rightarrow$ 4) glycosidic linkages with sulphate groups at C-2 that yields antithrombotic and anticoagulant activity [112]. The extracts of seaweeds show activated partial thromboplastin time (APTT) anticoagulant activity, which means that they are mostly effective on the intrinsic and/or common pathways of the coagulation cascade, particularly the extracts of the brown algae, *Laminaria digitata* and *Fucus vesiculosus*, and the red alga, *Chondrus crispus*. *L. digitata* [113]. Along with these, sulphated-fucans, extracted from *Sargassum vulgare* and *Ascophyllum nodosum*, also show anticoagulant and antithrombotic activity [114, 115]. Fucan with fucose sulphated at C-3 extracted from *Padina gymnospora* related to higher anticoagulant activity of heterofucan [112]. The activity is generally related to the molecular weight, charge density, chain length, and the three-dimensional structure of the sulphated polysaccharide that stimulates the coagulation proteins [116].

5.7. Anticarcinogenic and Antitoxic Activity. Low molecular weight (less than 10 kDa) fucoidan obtained by the degradation through gamma-irradiation without removal of sulphate group showed higher cytotoxicity in cancer cells such as HepG-2, AGS, and MCF-7 than high molecular weight fucoidan [117]. The activity of fucoidan by irradiation depends on its low molecular weight, degree of branching/chain conformation, and sulphate content [118]. Alginate and dietary fibre obtained from seaweeds protect from potential carcinogens [37]. Yamamoto et al. [119] investigated the idea that the hot water extract of brown seaweeds—such as *Sargassum fulvellum*, *Sargassum miyabei* (formerly *S. kjellmanianum*), *Saccharina angustata* (formerly *Laminaria angustata*), and *Saccharina longissima* (formerly *L. angustata* var. *longissima*)—contains a nondialyzable fraction of polysaccharide that suppresses the teratogenesis of sarcoma-180 cells hypodermically imbedded into mice. Polysaccharides of *Sargassum wightii* were extracted, and two fractions were obtained that inhibited the proliferation and migration of breast cancer cells [120]. Fucoidans are sulphated polysaccharides extracted from brown seaweeds like *Sargassum wightii*, which helps in the suppression of ontogenesis and migration of MDA-MB-231 human breast cancer cells and DMBA-induced tumors in rats by downregulating the PI3 K/AKT/GSK3b pathway [121]. Polyphenols such as phlorotannins and diterpenes synthesized from *Desmarestia* and *Dictyota* possesses anticarcinogenic activity [122]. Along with this, a bioactive diterpene from *Desmarestia ligulata* and *Dictyota dichotoma* reported a strong cytotoxic effect against leukemia cell lines [123]. Dichloromethane extracts from *Dictyota kunthii* and *Chondracanthus chamissoi* reported cytotoxicity against HT-29 and MCF-7 cell lines [124]. Secondary metabolites from *Sargassum* sp. (*S. angustifolium*, *S. oligocystum*, and *S. boveanum*) such as plastoquinones, polysaccharides, chromanols, tannins, flavonoids, sterols, saponins, and

TABLE 3: Seaweed with various antiviral compound and its function.

Seaweed	Antiviral compound	Function	References
Green seaweeds			
<i>Ulva lactuca</i> (as <i>Ulva fasciata</i>)	Sphingosine, N-palmitoyl-2-amino 1,3,4,5-tetrahydroxyoctadecane	Prevents from Semliki Forest virus (SFV)	Garg et al. [85]
<i>Halimeda tuna</i>	Halitunal (diterpene)	Prevents from murine coronavirus A59	Koehn et al. [86]
<i>Caulerpa racemosa</i>	Sulquinovosyldiacylglycerol	Prevents from herpes simplex virus 2 (HSV-2)	Wang et al. [87]
<i>Monostroma latissimum</i>	Rhamnan sulphate	HSV-1, HCMV, HIV-1	Lee et al. [88]
Brown seaweeds			
<i>Dictyota friabilis</i> (formerly <i>Dictyota paffii</i>)	Dollabelladiene derivative and 10,18-diacetoxy-8-hydroxy 2,6-dollabeladiene	Anti-HSV-1 activity, inhibits HIV-1 reverse transcriptase	Ireland and Faulkner [89]; Barbosa et al. [90]
<i>Ecklonia cava</i>	Phlorotannin derivatives (8,80-bieckol and 8,400-bieckol)	Inhibits HIV-1 reverse transcriptase (RT) and protease [34]	Fukuyama et al. [91]
<i>Adenocystis utricularis</i>	Fucoidan	HSV-1, HSV-2	Ponce et al. [84]
<i>Ishige okamurae</i>	Sulquinovosyldiacylglycerol	Prevents from herpes simplex virus 2 (HSV-2)	Wang et al. [87]
<i>Leathesia marina</i> (formerly <i>Leathesia difformis</i>)	Fucoidan	HSV-1, HSV-2	Feldman et al. [92]
<i>Sargassum horneri</i>	Fucoidan	HSV-1, HCMV, HIV-1	Hoshino et al. [93]
<i>Fucus vesiculosus</i>	Fucoidan	HIV	Béress et al. [94]
<i>Silvetia compressa</i> (formerly <i>Pelvetia fastigiata</i>)	Fucoidan	HBV	Venkateswaran et al. [95]
Red seaweeds			
<i>Gracilaria corticata</i>	Sulphated agarans	HSV-1, HSV-2	Mazumdar et al. [96]
<i>Chondracanthus tenellus</i> (formerly <i>Gigartina tenella</i>)	Sulquinovosyldiacylglycerol, a new sulfolipid KM043	Potent inhibitor of eukaryotic DNA and HIV-1 reverse transcriptase type 1	Ohata et al. [97]
<i>Laurencia venusta</i>	Venustatriol, thyrseferol, and thyrseferyl 23-acetate	Prevents from vesicular stomatitis virus (VSV) and herpes simplex virus type 1 (HSV-1)	Sakemi et al. [98]
<i>Nothogenia fastigiata</i>	Xylomannan and xylogalactan	Inhibits the multiplication of HSV-1 and HSV-2	Domente et al. [82]
<i>Gymnogongrus torulosus</i>	DL-hybrid galactans	HSV-2, dengue virus 2	Pujol et al. [99]
<i>Bostrychia montagnei</i>	Sulphated agarans	HSV-1, HSV-2	Duarte et al. [100]
<i>Asparagopsis armata</i>	Sulphated agarans	HIV-1	Haslin et al. [101]
<i>Stenogramme interrupta</i>	Carrageenans	HSV-1, HSV-2	Cáceres et al. [102]
<i>Cryptopleura ramosa</i>	Sulphated agarans	HSV-1, HSV-2	Carlucci et al. [103]
<i>Sarcopeltis skottsbergii</i> (formerly <i>Gigartina skottsbergii</i>)	Lambda-, kappa/iota-, and carrageenans	HSV-1, HSV-2	Carlucci et al. [104]; Carlucci et al. [105]
<i>Pterocladia capillacea</i>	Sulphated agarans and DL-hybrid galactans	HSV-1, HSV-2, HCMV	Pujol et al. [106]
<i>Agardhiella subulata</i> (formerly <i>Agardhiella tenera</i>)	Sulphated agarans	HIV-2, HIV-1, HSV-1, HSV-2, HCMV, VSV, inf A, RSV, vaccinia, togaviruses, parainfluenza virus	Witvrouw et al. [107]
<i>Schizymenia dubyi</i>	Sulphated galactans with uronic acids	HIV-1, HSV-1, HSV-2, VSV	Bourgougnon et al. [108]
<i>Schizymenia pacifica</i>	Lambda-carrageenan	HIV-1, AMV	Nakashima et al. [109]

triterpenes showed strong toxicity against MCF-7, HT-29, and HeLa cell lines [125]. Drug (Detoxal) developed from the calcium alginate extract of brown seaweeds reduces the level of lipid peroxidation products, has antitoxic effects on hepatitis, and also normalizes the lipid and glycogen level in the liver [37].

6. Seaweed as Food Product Supplement

6.1. Nori. The purple laver (red seaweed), *Porphyra/Neoporphyra/Pyropia/Neopyropia* genera, contains nearly 50 species in the world, of which 20 species are found in Japan that are used as seaweed food called nori [7]. The most

common species used for nori are *Neopyropia tenera* (formerly *Porphyra tenera*), *Neopyropia yezoensis* (formerly *Porphyra yezoensis*), *Pyropia columbina* (formerly *Porphyra columbina*), and *Porphyra umbilicalis* [31]. In Japan, the dried sheets of laver (*Porphyra* sp.) are used to cover rice balls containing vegetables in sushi rice. Currently, nori is mixed with ready-to-eat foods such as wine, instant soup, and jam to enhance their nutritional content [7]. As per nutritive value, nori seaweed (*Porphyra* sp.) is rich in vitamin B complex mainly in vitamins B₆ and B₁₂ [126], dietary fibre, and protein content which are higher in *Pyropia columbina*. The main fatty acids present are palmitic and eicosapentaenoic acid. It also has high mineral content such as sodium and potassium with intermediate levels of phosphorus, calcium, and zinc [127]. Nori as food provides many health benefits. One such role is associated with the regeneration of red blood cells and decrease in the risk of pernicious anaemia. It also contributes to the normal working of the human neural network and development of the body [31].

6.2. Kombu. Kombu belongs to the class Phaeophyceae or kelps (large brown seaweed). The most common species of *Laminaria/Saccharina* are called kombu viz., *Saccharina latissima* (formerly *Laminaria saccharina*), *Saccharina japonica* (formerly *Laminaria japonica*), and *Saccharina angustata* (formerly *Laminaria angustata*). At a commercial level, kombu items are processed in a dried form and rehydrated in water before use. It is used in the preparation of soup, salads, and condiments [31]. As per nutritive value, *Saccharina japonica* (formerly *Laminaria japonica*) consists of alginate gel network and cellulose, including fucoidan and glycoprotein. It is a good source of calcium, sodium, iron, potassium, iodine, and phosphate minerals [128]. It is also a rich source of glutamic acid which is responsible for the “umami” taste [31].

6.3. Wakame. Wakame also belongs to class Phaeophyceae, which is a kelp that is used as food mostly in Japan and China. The most common species of *Undaria* are *Undaria pinnatifida* are used in soup preparation such as miso soup in Japan and as side salads with tofu. It is a good source of polysaccharide (fucoidan) and xanthophyll (fucoxanthin) and is rich in soluble dietary fibre that is used as supplement for weight loss [31].

6.4. Sea Lettuce. Sea lettuce belongs to the class Chlorophyta. Common species of *Ulva* are *Ulva lactuca*, *Ulva rigida*, and *Ulva lactuca* (formerly *Ulva fasciata*) which are consumed in raw form or in soup preparations. It has high protein, high soluble dietary fibre content, and moderate value of vitamins and minerals such as iron. It is used as a health supplement such as in multivitamins [31].

6.5. Seaweed Soup. Jayasinghe et al. [129] developed an instant seaweed-vegetable soup with ingredients (cereals, legumes, and seaweed extracts (agar or carrageenan)) used it

as a food substitute to replace pectin. Seaweed is enriched with minerals (iodine) and polysaccharides which improve the viscosity and overall nutritive values of the soup. It was found that iodine concentration is higher in the seaweed-vegetable soup than commercial vegetable soup and, therefore, prevents thyroid problems if the former is consumed. Therefore, this can be recommended as a functional food for iodine-deficient patients.

6.6. Seaweed Chocolate. Thahira Banu et al. [130] developed a high iron content chocolate incorporated with green seaweed (*Ulva reticulata*) that contains 40–50% of the iron content of the total mineral content of seaweed. Value-added chocolate can thus be developed to supplement anaemic adolescent humans.

6.7. Seaweed Pickle, Pakoda, and Halwa. Sumayaa and Kavitha [131] prepared seaweed pickle, pakoda, and halwa in which dry seaweeds powder of *Eucheuma*, *Ulva reticulata*, and *Sargassum wightii* was incorporated in various levels. The nutrient content of seaweed incorporated recipes was higher than nonincorporated seaweed recipes in terms of proximate composition, minerals, and pigments [131]. Iron-rich seaweed foods increase the haemoglobin content in the body and carotene acts as an antioxidant to scavenge free radicals and oxygen [131].

6.8. Seaweed Spices. The study conducted by Amudha et al. [132] developed spice adjunct containing edible red seaweed *Eucheuma* (earlier *Kappaphycus alvarezii*) as an ingredient. Seaweed-spice adjunct showed an increase in the protein (by 10%), crude fibre content (by 9.4%), and ash content (22.2%) with high amounts of vitamin E and trace amounts of niacin and vitamin B₂ [132]. Therefore, seaweed spices could be good sources of vitamins and proteins that are useful to reduce oxidative stress in the body [132].

6.9. Seaweed Pasta. Prabhasankar et al. [133] developed pasta with Japanese seaweed, wakame (*Undaria pinnatifida*), and Indian brown seaweed (*Sargassum marginatum*) which was acceptable with better functional activity. They reported that fucoxanthin was not affected by the pasta making process [133] and antioxidative properties of seaweed incorporated pasta did not reduce with increasing seaweed content (>2.5%) [134].

6.10. Seaweed Noodles. Chang and Wu [135] in their study incorporated green seaweed (*Monostroma nitidum*) powder in different proportions with or without eggs to develop noodles. Chang and Wu [135] reported that breaking energy, springiness, and extensibility of freshly cooked noodles reduced, and cooking yield increased significantly with the incorporation of increased concentrations of seaweed [135]. Keyimu [136] incorporated *Gracilaria* seaweed powder to develop alkaline noodles with high nutritional quality that were rich in fibre content.

6.11. Seaweed Wafer, Porridge, Jelly, and Jam. Kaliaperumal [137] studied the preparation of seaweed-based wafer, porridge, and jelly from the red seaweed *Hydropuntia edulis* (formerly *Gracilaria edulis*) and preparation of jam from *Ulva lactuca* [137].

6.12. Seaweed Coffee. Kumar et al. [11] prepared seaweed infused coffee from Indian brown seaweed (*Sargassum wightii*) with 1%, 3%, and 5% seaweed powder. They reported that, with an increase in the concentration of seaweed in coffee, there is an increase in antioxidant activity. Along with this, Kumar et al. [11] analysed thermal, spectral, and rheological characteristics of seaweed coffee. The authors found that all the seaweed coffee samples were acceptable from a sensory standpoint.

6.13. Seaweed Cookie and Sauce. Oh et al. [138] reported the preparation of seaweed cookies from four different Korean seaweeds, viz., *Ulva linza* (formerly *Enteromorpha linza*), *Codium fragile*, *Sargassum fulvellum*, and *Sargassum fusiforme* (formerly *Hizikia fusiformis*). Cookies prepared from 5% seaweed powder were found to be similar to the control in spread factor, moisture content, and flavor (masking the fishy smell of seaweeds).

Afonso et al. [27] incorporated brown seaweed *Gongolaria abies-marina* (formerly *Treptacantha abies-marina*) for cookie and sauce preparation. Sauces and cookies differed in their elemental composition, whereas minerals (K, Ca, Mg, Na, P, and Zn), phenolic content, and antioxidant activity were present in higher quantities in the sauces. Also, 3% incorporation of seaweed in cookie and 2% in sauce were found to be acceptable.

7. Future Prospects

Caulerpa racemosa, *Ulva lactuca* (formerly *Ulva fasciata*), *Chnoospora minima*, *Padina gymnospora*, and *Acanthophora spicifera* are good sources for amino acids and are rich in lysine and methionine amino acids. Therefore, these seaweeds are utilized for the formulation of highly nutritive food products with cereals and legumes such as seaweed-based bread, biscuits, and idly which provide a balanced diet to the individual.

Not only is acceptability of nutrient-rich seaweeds scarce, but also the processed food industry has not utilized them effectively to develop seaweed-based functional food products and nutraceuticals. Also, agricultural conditions are becoming hostile due to rapid urbanization and climate change which results in a reduction of agriculture produces. Therefore, seaweed-based food is one such unexplored area that needs attention and can provide a suitable solution for this problem. Also, products formed from sulphated polysaccharides (agar, carrageenan, fucoidan, laminaran, and ulvan) of seaweeds may vary in their chemical composition because it depends on hostile environmental conditions such as location and time of harvest. Therefore, there is a need to

standardize the commercial product prepared from an algal polysaccharide. Also, sulphated polysaccharides from seaweeds may be used as encapsulating material for micro- and nanoencapsulation-based applications.

There is a need to optimize the methods for extraction, quantification, and purification of bioactive compounds (fucoidan, ulvan, fucoidan, and phloroglucinol) from seaweeds. The combination of bioactive components of seaweed with drugs acts as high-value therapeutic agents which may significantly reduce the ill effects on health. To find the possibility of incorporating seaweeds in food for the development of value-added products, the antimicrobial activity of the seaweed against bacteria and fungi should be carried out.

Toxicity, allergen, and microbial studies should be examined for seaweeds before utilization to develop functional foods. The effect of incorporation of seaweeds in a food item and changes in physicochemical characteristics during processing and interaction with body metabolism is also an interesting idea that needs to be evaluated through *in vivo* studies.

Different types of seaweeds such as *Gracilaria*, *Sargassum*, *Ulva*, and *Eucheuma* have been used in different varieties of foods (noodles, pasta/coffee, pickle, and spices, respectively) for the development of seaweed-based food and beverages. Therefore, to enhance seaweed application in food, more research will be needed to know the processing technologies, compositional standards, and human gut interaction.

8. Conclusions

The present findings provide information on the antioxidant potential, nutritional value, and therapeutic activity of seaweeds that will be helpful for the development of seaweed-based food and supplements for the food industry. The incorporation of seaweeds in food may solve health problems emerging as a result of protein, mineral, and carbohydrate deficiencies. The bioactive compounds extracted from seaweeds provide multifold therapeutic activities (antitumor, anticancer, antithrombin, etc.) that make it essential to popularize the use of seaweeds in commercial food products as a natural source of antioxidants.

Data Availability

All data used to support this study are available within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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