

## **Nutritional value of marine seaweeds and their potential to serve as nutraceutical supplements**

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### **Abstract**

Seaweeds are marine autotrophic organisms with numerous bioactive compounds of interest. Several seaweed products are available in the form of food or medicine due to their myriad beneficial biomolecules like anti-diabetic, anti-inflammatory and antioxidants compounds. The information presented herein gives an overview about the current knowledge of seaweed nutritional values and their potential application as nutraceutical supplements for health benefits in terms of mineral contents, vitamins, fatty acids, antioxidants, and dietary fibres. Seaweeds rich in essential fatty acids and vitamin B<sub>12</sub> (cobalamin) can be an alternative food for vegetarians, as vegetables and fruits are poor sources of these elements. The seaweed-based functional food products and supplements have great potential health benefits and can potentially help to improve malnutrition.

**Keywords** :antioxidant; bioactive molecules; dietary fibres; nutrition; polysaccharides;seaweed; vitamins.

## Introduction

Seaweeds contain major macronutrients like carbohydrates, protein and lipids, vitamins and other micronutrients, and numerous biologically active compounds, such as polyphenols (Pereira 2011). Some of these bioactive compounds are derived from biomass structural constituents, such as carbohydrates, protein, fatty acids, and others as a by-product of biochemical processes such as sterols, polyphenols. However, the nutritional properties and biochemical composition of seaweeds can be affected by seasonality, geographic location and species (Marinho *et al.* 2015; Zhou *et al.* 2015; Nunes *et al.* 2017; Kumar *et al.* 2018; Circuncisão *et al.* 2018). Bioactive molecules of seaweeds have been observed to exert positive effects on high-incidence chronic diseases such as arteriosclerosis, coronary heart disease, thrombosis and apoplexy (Cardoso *et al.* 2015; Collins *et al.* 2016). Considering their biological activity and the mechanisms involved in their absorption, biologically active compounds are broadly divided into two groups: i) non-absorbed high molecular substances like dietary fibres, and ii) low molecular substances, which are absorbed and affect the human homeostasis directly (Holdt & Kraan 2011).

Seaweeds are a rich source of bioactive molecules with potential as nutritional supplements, pharmaceuticals, cosmeceuticals, fine chemicals and enzymes (Pereira 2018a, b; Penalver *et al.* 2020). Seaweed nutraceuticals, defined as food and food products that have been demonstrated to produce health-promoting benefits, can lower the risk of chronic diseases such as obesity, diabetes, heart disease, and cancer. Hence, they enhance the ability of chronic disease management and improve the quality of life (Holdt & Kraan 2011; Shannon & Abu-Ghannam 2019). Due to various health-benefiting properties, there is a growing interest and recognition for seaweed nutraceutical supplements and functional foods. A recent study indicated that countries where people regularly consume seaweeds suffer less from obesity and diet-related ailments (Nanri *et al.* 2017). The consumption of fibre-rich seaweeds and derived supplements is known to boost appetite, satiety and lowers the cholesterol and glycaemic index (Brown *et al.* 2014). The undesirable side effects of allopathic drugs also make nutraceutical supplements an attractive alternative in palliative care such as biliary tract, breast and colon cancer (Nelson *et al.* 2017). Regular intake of seaweeds can greatly reduce the risk of these cancers, attributed to bioactive compounds such as fucoxanthin, polyphenols, phlorotannins, antioxidants, and sulfated polysaccharides (fucoidan), as these compounds can induce apoptosis in cancer cells (Namvar *et al.* 2012; Gutiérrez-Rodríguez *et al.* 2018; Jiang & Shi 2018). Besides, polyphenolic compounds, vitamin A, C and E are strong antioxidants (Shannon & Abu-Ghannam 2019), and bioactive compounds such as phlorotannins, fucoxanthin, polyphenolics and polysaccharides have effective antidiabetic properties (Murray *et al.* 2018). These latter compounds

inhibit hepatic gluconeogenesis and reduce the activity of the digestive enzymes such as  $\alpha$ -amylase, lipase and aldose reductase (Sharifuddin *et al.* 2015; Shannon & Abu-Ghannam 2019). Omega 3-fatty acids (eicosapentaenoic and docosahexaenoic acids) of seaweeds play an important role in reducing the risk of heart disease by influencing ionic channels within the cardiac cell membrane and maintaining intracellular calcium homeostasis (Kanoh *et al.* 2017).

The excellent quality of proteins (containing all essential amino acids), polyunsaturated fatty acids (omega-3 fatty acids), vitamins, minerals (magnesium and calcium), dietary fibres (alginates, agar and carrageenan), pigments (carotenes, xanthophylls and chlorophylls) and secondary bioactive metabolites (phytosterols and polyphenols) in seaweeds have attracted great interest in their nutritional use (Holdt & Kraan, 2011; Pereira 2018a, b). The growing demand for seaweed-based food supplements is further fuelled by their low caloric content. In East Asian countries like China, Japan and Korea, seaweeds have been used as food for centuries (Penalver *et al.* 2020). For instance, dried *Porphyra* spp and *Pyropia* spp (mainly from (*Porphyra umbilicalis*, *Pyropia tenera* and *P. yezoensis*) commonly called nori is a well-known seaweed food supplement in Japan (Baweja *et al.* 2016). In other parts of the world, consumption of seaweeds is not a common practice. But in recent years the perception towards seaweed is changing and they are considered as ‘superfoods’ because of their bioactive compounds (Cofrades *et al.* 2017).

Seaweeds also produce many primary and secondary metabolites which have great potential use as pharmaceuticals, nutraceuticals and cosmeceuticals (Pereira 2018a). The diverse bioactive compounds of seaweeds, nutritional values and the benefits ascribed are reviewed in this article. An exhaustive literature survey has been carried out using Google scholar and PubMed.

### **Nutritional value of seaweeds**

In recent years, studies on seaweeds have unveiled their nutritional value and their richness in essential molecules that benefit our health and wellness (Wells *et al.* 2017; Pereira, 2018a, b; Roleda & Hurd 2019; Cikoš *et al.* 2020; Penalver *et al.* 2020). Proximate composition analysis of seaweeds indicate high levels of carbohydrates, minerals, vitamins, dietary fibres, essential fatty acids, carotenoids, and trace elements like iodine (Holdt & Kraan 2011; Tabarsa *et al.* 2012; Syad *et al.* 2013; Circuncisão *et al.* 2018). For instance, the vitamin C levels in *Porphyra umbilicalis*, *Himanthalia elongata*, and *Gracilaria changii* are comparable to vitamin C found in tomatoes and lettuce (Ferraces-Casais *et al.* 2012). Seaweed polysaccharides are the most exploited and widely used seaweed molecules (Bilal & Iqbal 2020). The stabilizing and texture-giving properties of polysaccharides are extensively used in the food industry (Cotas *et al.* 2020a). The nanocellulose derived from seaweeds has multiple

applications, and the biocomposites developed from these are used for controlled drug release (Ditzel *et al.* 2017).

Compound concentrations can vary with season and seawater temperature (Nunes *et al.* 2017). Seaweeds from different geographical regions can exhibit varying elemental composition (Chen *et al.* 2018) and when grown in industrial and sewage contaminated areas can pose a risk to human health (Wang *et al.* 2013). The regular consumption of seaweeds harvested from such areas is detrimental to human health mainly due to heavy metal content (Burger *et al.* 2012; Cherry *et al.* 2019). However, a study by Rubio *et al.* (2017) indicated that for the majority of seaweeds levels of heavy metals are within the food safety limit and overall represent a low health risk. Still, they advised continuous surveillance and assessment to meet safety regulations. Following this advice, the diverse nutritional elements make seaweeds an attractive functional food and nutraceutical supplement.

### **Dietary fibres**

Fibres of seaweeds are polysaccharides of mainly two types: structural (cellulose, hemicellulose and xylans), and storage polysaccharides (carrageenan, alginate and agar). These polysaccharides and hydrocolloids have no nutritional value, as humans lack the enzymes to metabolize them, but as dietary fibres they can play an important role in a healthy nutrition (Penalver *et al.* 2020).

The addition of dietary fibres to the diet reduces the transit time of faeces through the digestive tract by promoting bowel movement and lowers the risk for colorectal cancer by diluting faecal carcinogens and by promoting the production of short-chain fatty acids with anti-carcinogenic properties (Holdts & Kraan 2011; Penalver *et al.* 2020). The low incidence of colorectal cancer in Japan, for example, has been attributed to the regular intake of seaweeds containing high fibre (Moussavou *et al.* 2014). Other health benefits of dietary fibres include a reduction in cardiovascular disease and obesity and the intake of fibres also gives the feeling of contentment and satiety (Jiménez-Escrig *et al.* 2013; Penalver *et al.* 2020). The recommended fibre intake in the US and the UK is in the range of 18–30 g, which can be fulfilled by incorporating seaweed in the diet (Rajapakse & Kim 2011; Circuncisão *et al.* 2018). Fibres constitute about 36–60% of seaweed biomass (Circuncisão *et al.* 2018), comparable to, and in some cases exceeding that of fruits and vegetables (Table 1). The values of fibres (5–10 g per 100 g dw) found in *Porphyra columbina*, for example, is comparable to that of land vegetables (Cian *et al.* 2014). Similarly, the fibre content in Kombu (*Laminaria digitata*) (6.2%) is higher than that of brown rice (3.8%; McCance & Widdowson 2014).

Seaweed polysaccharides have numerous beneficial properties such as probiotic activity, inhibition of viruses, suppression of gastrointestinal inflammation, anticancer properties, reduction in

cholesterol uptake and anti-glycosidase activity (Rajapakse & Kim 2011; Wang *et al.* 2012; Necas & Bartosikova 2013; Cotas *et al.* 2020b; Daub *et al.* 2020). In addition, seaweed fibres contain negligible amounts of starchy carbohydrates, resulting in a lower glycaemic load, which is beneficial in regulating the glycaemic index of diabetic patients (Wee & Henry 2020).

Seaweeds contain both soluble and insoluble fibres. Soluble fibre content tends to be higher in red seaweeds such as *Chondrus* and *Porphyra* sp. than brown and green seaweeds (Holdts & Kraan 2011; Penalver *et al.* 2020), whereas brown seaweeds such as *Laminaria* sp. *Saccharina* sp. and *Fucus* sp. have higher insoluble fibre content (Penalver *et al.* 2020). Soluble fibres of seaweeds are known to produce short-chain fatty acids (SCFAs) such as acetate, propionate and butyrate in the large intestine due to fermentation (Cantarel *et al.* 2012). SCFAs nourish the epithelia of the large intestine and modify the intestinal microbiome (Cian *et al.* 2015). In addition, partially digested seaweed proteins and carbohydrates in the small intestine can stimulate the immune response in humans by indirect promotion of microbial response (Cian *et al.* 2015; Wells *et al.* 2017).

### **Mineral content (inorganic elements)**

Minerals are essential for our body to develop and function normally, and seaweeds are a good source of these minerals (Mišurcová *et al.* 2011). Seaweeds contain a variety of minerals such as iron (Fe), iodine (I), calcium (Ca), magnesium (Mg), copper (Cu), manganese (Mn) and zinc (Zn) that are important micronutrients needed for human nutrition (Circuncisão *et al.* 2018; Cherry *et al.* 2019; Penalver *et al.* 2020) (Table 2). The mineral content in seaweeds is similar to that of seawater but varies between species and is affected by environmental factors such as season, salinity, pH, light, nitrogen source (Nunes *et al.* 2017; Circuncisão *et al.* 2018). A study showed that *Halimeda macroloba* contains 232 mg. 100<sup>-1</sup> g of calcium (Rattanasomboon *et al.* 2018), which equals ~23% of the Recommended Dose Intake (RDI) for an adult male. The total mineral content in *Galaxaura rugosa* is as high as 84.16 g. 100<sup>-1</sup> g dw (Nunes *et al.* 2017); 8 g of *Palmaria palmata* contain more iron than 100g of sirloin steak (McCance & Widdowson 2014). As such, the recommended dose of many essential minerals can be effectively met by consuming seaweed or from seaweed fortified foods.

Iodine regulates the metabolism and proper growth of the human body and is an essential constituent of thyroid hormones T3 (3,5,3-triiodothyronine) and T4 (thyroxine or 3,5,3,5-tetraiodothyronine). Thyroid hormones T3 and T4 regulate major metabolic processes such as catabolism of carbohydrates, lipids and protein, cellular respiration, thermoregulation, intermediary metabolism and nitrogen retention (Abbaspour *et al.* 2014; Nunes *et al.* 2018). Iodine deficiency results in metabolic disorders such as goitre and developmental delay, including mental retardation and brain

damage especially amongst children (Pearce 2012; Eastman & Zimmermann 2018). Consequently, iodine deficiency is recognised as an important global health issue (Biban & Lichiardopol 2017). Seaweeds are an excellent source of iodine; brown seaweeds contain the highest iodine content, with some species exceeding the RDI (150 µg per day) (Rajapakse & Kim 2011). Red and green seaweed species such as *Eucheuma cottoni*, *E. spinosum*, *Palmaria palmata*, *Porphyra* sp., *Ulva lactuca* also contain iodine but at lower concentrations (Zava & Zava 2011; Nitschke & Stengel 2016; Rasyid 2017; Cherry *et al.* 2019). Thus, the iodine requirement can be met by consuming seaweeds or seaweed-based nutraceutical supplements.

Zinc plays a vital role in the synthesis of DNA and RNA (Sharif *et al.* 2012), whereas Mn is required for several metabolic processes including blood clotting and hemostasis (Chen *et al.* 2018). Zinc and Mn coupled with Ca and Cu aid in improving bone mass density in postmenopausal women (Razmandeh *et al.* 2014). Osteoporosis is common among elderly people, so the requirement of these minerals can be fulfilled by the intake of seaweeds directly or as supplements. Manganese is also a constituent of an important antioxidant called superoxide dismutase (SOD). SOD protects against free radicals that cause cellular damage and contribute to aging, chronic kidney disease and heart disease (Kitada *et al.* 2020). Rich in Zinc are *Chondrus crispus*, *Porphyra umbilicalis* and *Gracilaria corticata*, *G. edulis* (Circuncisão *et al.* 2018), and *Chondrus crispus*, *Palmaria palmata* and *Gracilaria vermiculophylla* are rich in Mn (Parjikolaei *et al.* 2016; Circuncisão *et al.* 2018).

### **Fatty Acids**

Fatty acids are long-chained hydrocarbons and are broadly divided into four categories: saturated, monounsaturated, polyunsaturated and trans fats. Overall, lipids make up about 1–5% of seaweed dry weight (Penalver *et al.* 2020). A recent study showed that the lipid content of *Asparagopsis taxiformis* was 2.9–6.2 g per 100 g dw, which contributed about 9.5% to the RDI (Mellouk *et al.* 2017; Nunes *et al.* 2019). Polyunsaturated fatty acids (PUFA) constitute a significant part of the seaweed lipid profile (Penalver *et al.* 2020) (Table 3). The growing interest in seaweed-derived polyunsaturated fatty acids is mainly ascribed to the presence of  $\omega$ -3 and  $\omega$ -6 PUFA (Kendel *et al.* 2015; Goncalves *et al.* 2017; Alencar *et al.* 2018; Michalak 2018).

Fatty acids influence many biological activities such as the regulation of membrane structure and function, intracellular signalling and gene expression (Gonçalves *et al.* 2017). Particularly important are essential fatty acids (EFAs) because they are not synthesized in the human body and are important for immunomodulation, brain development, cellular signalling, regulation of transcription factors, prevention of cancers such as breast, prostate, colon and renal cancer, cardiovascular,

neurodegenerative and autoimmune diseases, and inflammation due to rheumatoid arthritis (Imhoff-Kunsch *et al.* 2011; Cardoso *et al.* 2015; Cornish *et al.* 2017; Goncalves *et al.* 2017; Cotas *et al.* 2020a) (Table 4). Essential fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid ( $\omega$ -3 fatty acids) are also known to protect from dementia and suppress inflammation in patients with rheumatoid arthritis (Cotas *et al.* 2020a). Red seaweeds are a particularly good sources of several essential fatty acids such as eicosapentaenoic acid (20:5 $\omega$ -3), arachidonic acid (20:4  $\omega$ -6), linoleic acid (18:2  $\omega$ -6),  $\alpha$ -linolenic acid (18:3  $\omega$ -3) and stearidonic acid (18:4  $\omega$ -3) (Galloway *et al.* 2012), and several studies on health benefiting properties of seaweed derived fatty acids indicate promising potential nutritional and nutraceutical applications (Rajapakse & Kim 2011; Belattmania *et al.* 2018; Cherry *et al.* 2019; Shannon & Abu-Ghannam 2019).

## **Vitamins**

Vitamins, except D and K, are mainly obtained through animal-sourced food products such as meat, fish, eggs and dairy, as the human body does not produce these vitamins. Vitamin D is synthesized in the skin with the help of ultraviolet light and can be supplied as supplements, whereas vitamin K is produced in the intestine by bacteria (McKenna & Murray 2014).

Seaweeds contain both water-soluble and fat-soluble vitamins (Leandro *et al.* 2020). Seaweed vitamins such as thiamine, riboflavin, beta-carotene and tocopherols can reduce the risk of heart disease, thrombosis and atherosclerosis (Kong *et al.* 2018; Fischer 2019). Vitamin B<sub>12</sub> is an essential water-soluble vitamin and regulates the production of red blood cells and DNA (Koury 2016; Green *et al.* 2017). Unlike terrestrial plants, seaweeds are a good source of vitamin B<sub>12</sub>. *Ulva lactuca* and *Pyropia yezoensis* can produce biologically available vitamin B<sub>12</sub> (Watanabe *et al.* 2014) (Table 5). The vitamin B<sub>12</sub> found in *Pyropia* sp. is approx. 1 g. kg<sup>-1</sup> fresh weight (Castillejo *et al.* 2018), indicating that seaweeds can be a reliable source of vitamin B<sub>12</sub>.

Some seaweed species are also known to contain vitamins like vitamin E and K. The concentration of vitamin E, an important antioxidant is reported to be higher (1.16 mg. kg<sup>-1</sup>) in *Undaria pinnatifida* than in peanuts (0.8 mg. kg<sup>-1</sup>) (McCance & Widdowson 2014). Vitamin E and K are also found in *Grateloupia turuturu* (Kendel *et al.* 2013).

## **Proteins**

Proteins are essential for growth and repair as they form the structural and functional elements of cells in the body (Blanco & Blanco 2017). Green and red seaweeds have higher protein contents than brown seaweeds, as high as 47% of their dry weight (Černá 2011; O'Connor *et al.* 2020). *Porphyra* spp,

*Pyropia* spp, *Palmaria palmata*, and *Ulva* spp are the protein richest seaweeds (Pereira 2011; Taboada *et al.* 2013; Angell *et al.* 2016).

Aspartic and glutamic acid are the principal amino acids of seaweed proteins. The unique taste of umami is due to glutamic acid present in the seaweed *Laminaria japonica*. The flavour of umami formed the basis for the synthesis of monosodium glutamate (Druehl 2013). Monosodium glutamate is one of the most used flavour enhancers, and although its use is recognized as safe, it remains controversial (Zanfirescu *et al.* 2019). Some essential amino acids like histidine in *Ulva lactuca* are comparable to egg protein (Shuuluka *et al.* 2013). Seaweed proteins contain all the essential amino acids (Diniz *et al.* 2011), but they can vary with species, seasons and geographic location (Circuncisão *et al.* 2020).

Essential amino acids help to build up muscles, support their functioning and regulate the blood sugar level (Breitman *et al.* 2011; Hayashi *et al.* 2018). Amino acids are normally obtained from non-vegetarian diets such as meats, eggs and fish. Essential amino acids such as leucine, valine and threonine are rich in red seaweed species such as *Porphyra dioica*, *Porphyra umbilicalis* and *Gracilaria vermiculophylla* (Machado *et al.* 2020). Pepsin is a principal protein-digesting enzyme that helps to absorb amino acids in the small intestine. Pepsin obtained from *Pyropia yezoensis* exhibits numerous health benefiting properties such as angiotensin-converting enzyme (ACE) inhibitory effect, antimutagenic, anti-diabetic, inhibition of calcium precipitation, reduction of cholesterol levels, antioxidant activity and improvement of hepatic function (Harnedy & Fitzgerald 2011; Admassu *et al.* 2018).

### **Chlorophyll a**

Chlorophylls are green lipid-soluble pigments in seaweeds, higher plants and cyanobacteria for photosynthesis (Holdts & Kraan 2011) (Table 5). Besides, chlorophyll has an antioxidant property that can be useful as nutritional as well as health supplement (Tumolo & Lanfer-Marquez 2012; Pérez-Gálvez *et al.* 2020). Seaweeds contain different types of chlorophylls (chl), such as chl *a* and *b* in green seaweeds, chl *a* in red seaweeds, and chl *a* and *c* in brown seaweeds (Takaichi 2013). Chlorophylls are normally included in our diet by consuming green vegetables. A study by Vaňková *et al.* (2018) showed that chlorophylls have an antiproliferative effect in pancreatic cell lines. They observed that chlorophylls inhibited heme-oxygenase (HMOX) activity, which subsequently affected the redox environment of pancreatic cancer cells and suppressed their proliferation. Chlorophyll degradation products, such as pheophytin, pyropheophytin and pheophorbide have anti-cancer properties (Holdt & Kraan 2011).

## Carotenoids

Carotenoids are tetraterpenoid pigments present in plants, bacteria, fungi, and seaweeds. Major seaweed carotenoids are  $\alpha$ -carotene,  $\beta$ -carotene, lutein and zeaxanthin. Alpha- and  $\beta$ -carotene is the precursor of vitamin A. It plays an important photoprotective role against damage by reactive oxygen species (ROS) (Pérez-Gálvez *et al.* 2020) and exhibits numerous biologically active properties such as antioxidant, anti-inflammatory and antitumor activity (Di Tomo *et al.* 2012; Galasso *et al.* 2017; Viera *et al.* 2018). Carotenoids like lutein and zeaxanthin prevent the progress of age-related macular degeneration (Murray *et al.* 2013; Wu *et al.* 2015; Buscemi *et al.* 2018).

The reactive oxygen species (ROS) that accumulate during metabolic processes cause oxidative damage (Nita & Grzybowski 2016; Pérez-Gálvez *et al.* 2020). The oxidative damage in humans results in degenerative diseases and cancer (Nita & Grzybowski 2016; Aggarwal *et al.* 2019). However, these reactive oxygen species are effectively eliminated by carotenoid antioxidants (Miyashita 2014; Rengasamy *et al.* 2015; Patlevič *et al.* 2016). Important carotenoids like lutein,  $\alpha$ -carotene and zeaxanthin are produced by *Asparagopsis taxiformis* (Holdt & Kraan 2011; Chan *et al.* 2015; Pereira 2015) and *Pyropia yezoensis* (Koizumi *et al.* 2018). The carotenoid content in the red seaweed *Gracilaria lanceola* is high (131 mg. 100 g<sup>-1</sup> dw) (Nunes *et al.* 2017).

## Beta Carotene

Beta carotene is a precursor of vitamin A (retinol), an essential vitamin that promotes a healthy immune system, good skin and eye health (Pérez-Gálvez *et al.* 2020). Beta carotene also has antioxidant properties that protect the body from free radicals produced by oxidation of other molecules (Boominathan & Mahesh 2015; Corsetto *et al.* 2020). Oxidative stress is believed to be a cause of cognitive decline (Kandlur *et al.* 2020), and  $\beta$ -carotene based antioxidants prevent the decline of cognition (Hira *et al.* 2019). In *Codium fragile* (199  $\mu$ g per g) and *Gracilaria chilensis* (114  $\mu$ g. g<sup>-1</sup>), the  $\beta$  carotene content exceeds that of carrots (Wells *et al.* 2017) (Table 5).

Nagayama *et al.* (2014) found a positive correlation between the intake of carotenoids with dietary supplements by lactating women and carotenoid content in breast milk, improving carotenoid supply to the developing child.

## Fucoxanthin

Fucoxanthin, a marine carotenoid, is a xanthophyll pigment in the chloroplast of brown seaweeds such as *Eisenia bicyclis*, *Laminaria japonica* and *Undaria pinnatifida* (Jung *et al.* 2012; Jang *et al.* 2018; Table 5). It is the most abundant carotenoid in nature, and the characteristic brown colour of brown seaweeds is due to this pigment. Fucoxanthin exhibits several bioactive properties such as strong

antioxidant capacity, anti-obesity, anticancer, antidiabetic, hepatoprotective activity and anti-inflammatory effect (Miyashita *et al.* 2011; Abdul *et al.* 2016). Although fucoxanthin contains numerous nutritional qualities and medicinal properties, the use of fucoxanthin is challenging due to its poor water solubility, chemical instability and low bioavailability (Zhang *et al.* 2015; Huang *et al.* 2017). It readily gets oxidised in pure form (Abu-Ghannam & Shannon 2017). Fucoxanthin will be easier to develop into a safe nutraceutical supplement with the development of new methods to improve stability and bioavailability (Zhang *et al.* 2015), such as the encapsulation in oil emulsion (Huang *et al.* 2017; Xiao *et al.* 2020). Tsuboi *et al.* (2011) showed that fucoxanthin reacts with nitrate and forms nitrofucoxanthin. This exhibited a strong inhibitory effect on Epstein–Barr virus and on human pancreatic carcinoma. Other bioactive properties of fucoxanthin that have potential health benefits are anti-osteoporotic effect (Koyama 2011), antihypertensive property (Abu-Ghannam & Shannon 2017) and protection against lipid peroxidation (Takashima *et al.* 2012). The study by Miyashita *et al.* (2011) showed that ingestion of fucoxanthin can improve insulin resistance and decrease blood glucose level.

The inclusion of fucoxanthin in dietary supplements can help to prevent lifestyle-related diseases such as atherosclerosis, diabetes, heart disease, obesity and stroke. However, more human clinical trials are necessary to determine the safety and recommended daily dosage (Zhang *et al.* 2015; Abu-Ghannam & Shannon 2017). Fucoxanthin derived from *Phaeodactylum tricornutum*, a microalga, is allowed by the food and drug administration (FDA) to be used in dietary supplements (Bae *et al.* 2020).

## **Phenolics**

Phenolic compounds are secondary metabolites, found mainly in brown seaweeds such as *Fucus*, *Ascophyllum* and *Sargassum* (Mekinić *et al.* 2019; Penalver *et al.* 2020). They are structurally diverse and different polyphenolic compounds such as bromophenols, flavonoids, phenolic terpenoids, etc. are found in brown seaweeds (Cotas *et al.* 2020b). Phenolics have attracted great attention in recent years due to their promising bioactivity of potential pharmacological applications and many other health-benefiting properties.

Phlorotannins are the most studied polyphenols of seaweeds, as they have many bioactive properties such as antioxidant, antidiabetic, and antibiotic properties. Consequently, they have been identified as potential candidates for the development of natural antioxidant-based functional foods (Farvin & Jacobsen 2013). Phlorotannins play important ecological functions such as cell wall hardening, protection against herbivory, protection against UV radiation, wound healing, as a chelating agent of toxic metals, adaptation to wave exposure and desiccation (Singh & Sidana 2013; Mannino

& Micheli 2020). The bromophenol present in *Gracilaria* sp. is antidiabetic, anticancer and antioxidant (Liu *et al.* 2011). The antioxidant activity of seaweed phlorotannins is more potent than that of polyphenols derived from terrestrial plants (Ferrerres *et al.* 2012; Vizetto-Duarte *et al.* 2016; Sellimi *et al.* 2017). The numerous bioactivities associated with polyphenolics, particularly of phlorotannins, provide many potential applications in nutraceutical, pharmaceutical and cosmeceuticals industries.

### **Sterols**

Sterols are another group of secondary metabolites with health benefits, showing antioxidant, antiviral, antifungal and antibacterial properties (Abdul *et al.* 2016). Fucosterols and desmosterols are the main sterols (Lopes *et al.* 2011), but some seaweeds sterols such as desmosterol, cholesta-4,6-dien-3-ol and cholest-5-ene-3,7-diol have cholesterol like properties (De Andrade Tomaz *et al.* 2012; Santos *et al.* 2015; Xu *et al.* 2015).

*Porphyra* sp. and *Osmondea pinnatifida* contain cholesterol (Lopes *et al.* 2011; Hernández-Ledesma & Herrero 2013). Cholesterol is essential for cellular activities as they increase the fluidity of cell membranes (Lopes *et al.* 2013). Fucosterols are antidiabetic, antioxidant, improve digestion and reduce cholesterol concentration in animals and humans (Christaki *et al.* 2013; Abdul *et al.* 2016; Mouritsen *et al.* 2017) (Table 6). The phytosterols of *Ulva armoricana* induce a cholesterol lowering effect by decreasing intestinal absorption of cholesterol (Kendel *et al.* 2015), and offer protection against colon, breast and prostate cancer by increasing immune system efficiency (Lopes *et al.* 2013; Shahzad *et al.* 2017). These qualities of seaweed sterols have applications in nutraceutical and pharmaceutical formulations to manage and regulate cholesterol for human health.

### **Species-specific molecules**

Some notable seaweed specific molecules such as laminarin, ulvan, porphyran, floridean starches are species-specific polysaccharides of brown (*Laminaria* sp.), green (*Ulva* sp.) and red (*Porphyra* sp.) seaweeds (Holdts & Kraan 2011; Penalver *et al.* 2020). These molecules have shown promising nutraceutical and pharmacological properties. Laminarin is a water-soluble polysaccharide, a bioactive compound with antioxidant, anticoagulant, anti-inflammatory, immunostimulatory, antitumor activities and it contributes to seaweed dietary fibres (Lee *et al.* 2012; Kadam *et al.* 2015a; Deleris *et al.* 2016; Zargarzadeh *et al.* 2020). The laminarin extracted from *Laminaria hyperborea* showed strong antimicrobial activity against Gram positive (*Staphylococcus aureus* and *Listeria monocytogenes*) and Gram negative (*Escherichia coli* and *Salmonella typhimurium*) bacterial strains (Kadam *et al.* 2015b). Porphyran is a complex sulfate-containing polysaccharide and its greatest health benefit lies in fibre. Porphyran possesses several active biological properties such as anti-inflammatory, antioxidant,

hypolipidemic and anticancer activity in humans (Jiang *et al.* 2012; Wang *et al.* 2017). Ulvan is a sulfated heteroglycan. Bioactivity such as antioxidant, antiviral, antilipidemic, immunoregulatory effects and antitumour activities have been observed (Thanh *et al.* 2016; Abou El Azm *et al.* 2019; Kidgell *et al.* 2019). Mycosporine-like amino acids (MAAs) are water-soluble and photostable secondary metabolites (La Barre *et al.* 2014). MAAs are known for their cosmeceutical use such as in sun care products due to their highly efficient ultraviolet protective capability (Thiyagarasaiyar *et al.* 2020). However, studies have demonstrated that MAAs also have other important bioactive properties like anti-inflammatory, immunomodulatory and antioxidant activities (Lawrence *et al.* 2018). The strong antioxidant activity of MAAs could effectively inhibit the oxidation of  $\beta$ -carotene and reduce lipid peroxidation that is involved in aging process (Chrapusta *et al.* 2017).

## **Conclusion**

The regular consumption of seaweeds reduces the occurrence of chronic diseases such as obesity and diabetes (Turan & Cirik 2018). This is attributed to the presence of numerous health-benefiting bioactive molecules essential for healthy wellbeing. Although seaweeds are consumed in very few countries, they can be used as an ingredient in various food products to enhance nutritional quality. This improvement of food products will alleviate malnutrition due to the growing scarcity of proteins and essential vitamins. In recent years, a better understanding of dietary science has led to increased incorporation of seaweeds into foods to improve the nutritional properties (Shannon & Abu-Ghannam 2019).

Malnutrition is common among young children, lactating and pregnant women, adolescents and poverty-stricken people. Poor nutrition in the early days is known to affect the cognitive development of the child (Prado & Dewey 2014; DiGirolamo *et al.* 2020). Incorporating seaweeds in our diet could be a panacea to counter malnourishment.

The constraint of food production and supply from terrestrial resources is expected to encourage consumption of seaweeds to meet the demand of increasing growth in the world population. Seaweed-based functional food products and nutraceutical supplements can potentially contribute to alleviate the chronic malnutrition problem. Seaweed-fortified food products are one promising route toward this goal.

The present review observed that many seaweeds are of diverse nutritional value, as they contain essential vitamins, proteins and minerals including trace elements. Further, the numerous health benefits of biomolecules make seaweeds an attractive natural resource for the development of novel nutraceutical and other functional food supplements. The growing consumer awareness of the positive

health impacts of edible seaweeds also make them an increasingly attractive nutritional source. The essential fatty acids and vitamin B<sub>12</sub> (cobalamin) of seaweeds would be an ideal vegetarian alternative, as vegetables and fruits are poor sources of these elements.

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## Tables

**Table 1.** Dietary fibre content in seaweeds.

Source	Fibre (% dry weight)		
	Soluble	Insoluble	Total
Seaweeds			
<i>Durvillaea antarctica</i> <sup>a</sup>	27.7	43.7	71.4
<i>Himanthalia elongata</i> <sup>a</sup>	25.7	7.0	32.7
<i>Saccharina latissima</i> <sup>a</sup>	17	13.1	30
<i>Sargassum fusiforme</i> <sup>a</sup>	33.9	16.3	49.2
<i>Undaria pinnatifida</i> <sup>a</sup>	30.0	5.3	35.3
<i>Caulerpa lentillifera</i> <sup>a</sup>	17.21	15.78	33
<i>Ulva lactuca</i> <sup>*</sup>	18	36	54
<i>Enteromorpha</i> spp <sup>a</sup>	17.2	16.2	33.4
<i>Gracilaria chilensis</i> <sup>b</sup>	24	36	59.8
<i>Gracilaria fisheri</i> <sup>c</sup>	18	43	61
<i>Gracilaria tenuistipitata</i> <sup>c</sup>	18	42	58
<i>Macrocystis pyrifera</i> <sup>b</sup>	6.4	44	50
<i>Chondrus crispus</i> <sup>a</sup>	22.25	12	34.25
<i>Grateloupia turuturu</i> <sup>a</sup>	48	12.3	60.3
<i>Porphyra</i> spp <sup>a</sup>	17.9	16.8	34.7
Food from terrestrial plants (g/100 g weight)			
Brown rice <sup>d</sup>	Na	Na	3.8
Bananas <sup>d</sup>	Na	Na	3.1
Lentils <sup>d</sup>	Na	Na	8.9
Apple <sup>d</sup>	5.9	8.3	14.2

Source: Benjama & Masniyom 2012<sup>c</sup>; McCance *et al.* 2014<sup>d</sup>; Sanz-Pintos *et al.* 2017<sup>b</sup>; Penalver *et al.* 2020<sup>a</sup>. Na – data not available

**Table 2.** Proximate composition of seaweeds and other foods.

Seaweeds (mg per 100 g wet wt)	Calcium	Potassium	Magnesium	Sodium	Copper	Iron	Iodine	Zinc
<i>Ascophyllum nodosum</i> <sup>a</sup>	900	4400	700	3900	Na	13.3	75–125	Na
<i>Laminaria digitata</i> <sup>a</sup>	1005	11,579	659	3818	<0.5	3.29	304	2
<i>Himanthalia elongata</i> <sup>a</sup>	909	6739	827	3700	Na	Na	Na	3.8
<i>Undaria pinnatifida</i> <sup>a</sup>	931	8669	1181	7064	<0.5	Na	25	1.74
<i>Caulerpa lentillifera</i>	1874	1143	1029	8917	0.11	21.4	Na	3.5
<i>Ulva rigida</i> <sup>a</sup>	525	1561	2094	1595	0.50	283	Na	0.60
<i>Jania rubens</i> <sup>a</sup>	42344	328	2987	1100	0.7	47.5	Na	2.63
<i>Palmaria palmata</i> <sup>a</sup>	1000	2700	200	1100	0.56	32	Na	2.85
<i>Porphyra umbilicus</i> <sup>a</sup>	687	1407	283	1173	Na	18.2	17	4.23
<i>Chondrus crispus</i> <sup>a</sup>	420	3184	732	427	<0.5	4	20–30	7.14
<i>Gracilaria vermiculophylla</i> <sup>b</sup>	0.4	4.9	0.31	Na	0.0015	0.04	Na	0.0024
Other foods (mg per 100 g wet wt)								
Soya beans <sup>c</sup>	200	Na	Na	Na	Na	6.0	Na	Na
Carrot <sup>c</sup>	140	Na	Na	Na	Na	0.8	Na	Na
Brown rice <sup>c</sup>	110.0	1160.0	520.0	258.0	1.3	12.9	Na	16.2
Milk <sup>c</sup>	115.0	140.0	11.0	55.0	Na	0.1	15.0	0.4
Sirloin steak <sup>c</sup>	9.0	260.0	16.0	49.0	0.1	1.6	6.0	3.1
Bananas <sup>c</sup>	6.0	400.0	34.0	1.0	0.1	0.3	8.0	0.2
Peanuts <sup>c</sup>	60.0	670.0	210.0	2.0	1.0	2.5	20.0	3.5

Source: Holdts & Kraan 2011<sup>d</sup>; McCance & Widdowson 2014<sup>c</sup>; Parjikolaei *et al.* 2016<sup>b</sup>; Penalver *et al.* 2020<sup>a</sup>. Na – data not available

**Table 3.** Content of fatty acids (FAs) in different seaweeds.

Seaweeds	(% of the total fatty acids)		
	PUFAs	$\omega$ 3 PUFAs	$\omega$ 6 PUFAs
<i>Himanthalia elongata</i> <sup>a</sup>	38	19	15
<i>Laminaria</i> sp. <sup>a</sup>	47	25	21
<i>Undaria pinnatifida</i> <sup>a</sup>	69	45	22
<i>Zonaria tournefortii</i> <sup>b</sup>	2	1.11	0.14
<i>Ulva armoricana</i> <sup>d</sup>	29	24	4
<i>Ulva lactuca</i> <sup>b</sup>	1.18	0.86	0.32
<i>Asparagopsis taxiformis</i> <sup>c</sup>	68	Na	Na
<i>Chondrus crispus</i> <sup>a</sup>	Na	7.2	8
<i>Gracilaria</i> sp. <sup>a</sup>	Na	Na	45
<i>Palmaria</i> sp. <sup>a</sup>	Na	Na	2
<i>Porphyra</i> spp <sup>a</sup>	16	7	8
<i>Soliera chordalis</i> <sup>d</sup>	15	5	10

Source: Holdts & Kraan 2011<sup>a</sup>; Kendel *et al.* 2015<sup>d</sup>; Mellouk *et al.* 2017<sup>c</sup>; Nunes *et al.* 2019<sup>b</sup>.  
Na – data not available

**Table 4.** Potential health benefits of seaweeds' polyunsaturated fatty acids (PUFAs).

Seaweeds	Health benefits	References
<i>Ulva lactuca</i>	Anticancer property	Wang <i>et al.</i> 2013
<i>Ulva armoricana</i>	Property to increase immune system and lower blood cholesterol, anticancer property against skin and colon cancer	Kendel <i>et al.</i> 2015
<i>Porphyra dioica</i> , <i>Palmaria palmata</i> , <i>Chondrus crispus</i>	Suppress inflammation in patients with rheumatoid arthritis, beneficial effect to asthmatic patient	Imhoff-Kunsch <i>et al.</i> 2011; Robertson <i>et al.</i> 2015
<i>Porphyra umbilicalis</i> , <i>Undaria pinnatifida</i>	Improved lipoprotein metabolism	Olivero-David <i>et al.</i> 2011; Shannon & Abu-Ghannam 2019
<i>Undaria pinnatifida</i>	Antiobesity	Okado <i>et al.</i> 2011
<i>Undaria pinnatifida</i> , <i>Porphyra purpurea</i>	Prevention of cardiovascular disease, anti-inflammatory, antiplatelets	Taboada <i>et al.</i> 2013
<i>Ulva rigida</i> , <i>Gracilaria</i> sp., <i>Fucus vesiculosus</i> , <i>Saccharina latissima</i>	Prevention of cardiovascular, neurodegenerative, osteoarthritis, diabetes and autoimmune disease	Cardoso <i>et al.</i> 2015; Simopoulos 2016; Goncalves <i>et al.</i> 2017; Neto <i>et al.</i> 2018;
<i>Gracilaria</i> spp, <i>Ulva lactuca</i>	Anti-inflammatory, anticancer activity against breast and bladder cancer	Wang <i>et al.</i> 2013; Da Costa <i>et al.</i> 2017

**Table 5.** Contents of vitamins (mg per 8 dry wt.) and bioactive compounds (mg per 100 g dry wt) in seaweeds.

Seaweeds	Vitamins			$\beta$ -Carotene	Chl a	Polyphenols	Fucoxanthin
	B <sub>12</sub>	C	E				
<i>Ascophyllum nodosum</i> <sup>a</sup>	16.4	81.8	Na	Na	Na	Na	Na
<i>Himanthalia</i> sp <sup>b</sup>	Na	46.7	2.24	4.3	150	232	0.9–18.6 <sup>d</sup>
<i>Laminaria digitata</i> <sup>b</sup>	0.5	1.35	0.28	2.2	153	14.2	27.4
<i>Sargassum horneri</i>	Na	Na	Na	Na	Na	Na	2.12 <sup>e</sup>
<i>Undaria pinnatifida</i> <sup>a</sup>	43	1847	Na	Na	Na	Na	4.96 <sup>f</sup>
<i>Palmaria palmata</i> <sup>b</sup>	1.84	0.6– 5.5	0.2–1.3	2	80.4	0.6	Na
<i>Porphyra umbilicalis</i> <sup>b</sup>	0.78	33.3	0.11 – .34	3.9	161.4	3.2	Na
<i>Ulva rigida</i> <sup>a</sup>	60	94.2	1.97	Na	Na	Na	Na
<i>Ulva</i> spp <sup>b</sup>	6.3	10.0	Na	20.4 <sup>c</sup>	93	56 <sup>c</sup>	Na

Source: Ferraces-Casais *et al.* 2012<sup>b</sup>; Fung *et al.* 2013<sup>f</sup>; Susanto *et al.* 2015<sup>e</sup>; Rajauria *et al.* 2017<sup>d</sup>; Nunes *et al.* 2017<sup>c</sup>; Cherry *et al.* 2019<sup>a</sup>. Na – data not available

**Table 6.** Biological activities of seaweeds' sterols and their potential health benefiting properties.

Types of sterols	Seaweeds	Health benefits	References
Fucosterol, desmosterol	<i>Macrocystis</i> sp., <i>Pyropia</i> sp., <i>Palmaria</i> sp.	Improve digestion, enhanced blood clearance, lowering of free and bound cholesterol	Yi <i>et al.</i> 2016; Mouritsen <i>et al.</i> 2017
Fucosterol, hydroperoxy-24-vinylcholesterol	<i>Ecklonia stolonifera</i> , <i>Eisenia bicyclis</i>	Inhibit butyrylcholinesterase, enzyme that involve in Alzheimer's disease, antiobesity, Antidiabetic	Jung <i>et al.</i> 2013a, b; Abdul <i>et al.</i> 2016
Fucosterol	<i>Dictyota ciliolata</i> , <i>Dictyopteris divaricata</i> , <i>Padina sanctae-crucis</i> , <i>Sargassum thunbergii</i> ; <i>Sargassum carpophyllum</i> , <i>Sargassum angustifolium</i> , <i>Turbinaria tricostrata</i> , <i>Chondria dasyphylla</i> , <i>Ulva flexuosa</i> ,	Anticancer	Khanavi <i>et al.</i> 2012; Kim <i>et al.</i> 2013; Caamal-Fuentes <i>et al.</i> 2014; Ji <i>et al.</i> 2014
Fucosterol	<i>Hizikia fusiformis</i> (= <i>Sargassum fusiforme</i> )	Anti-inflammatory	Jung <i>et al.</i> 2013a
Fucosterol, sarinosterol	<i>Sargassum fusiforme</i>	Hepatoprotective	Hoang <i>et al.</i> 2012; Chen <i>et al.</i> 2014
Fucosterol	<i>Sargassum longifolium</i> , <i>Turbinaria conoides</i> , <i>Himantalia elongata</i>	Anti-pathogenic, antifungal, antiviral	Kumar <i>et al.</i> 2010; Santayo <i>et al.</i> 2011; Rajendran <i>et al.</i> 2013
Fucosterol	<i>Laminaria japonica</i>	Hyperlipidemia	Lee <i>et al.</i> 2011