Seaweed a Superfood: a Nutrient-Rich Solution for Modern Diets

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Abstract
Seaweeds, also called macroalgae, are an abundant renewable resource that flourishes on India's northwest and southeast coasts. They create bioactive chemicals with a wide range of health benefits while thriving in a variety of harsh settings. Seaweeds supply vital materials, including agar, alginate, and carrageenan, and are widely used in industries for their gelling, stabilizing, and thickening capabilities. These are essential in the food, pharmaceutical, and other industries. Seaweed's rich nutritional profile is one of its main health advantages, particularly when it comes to treating vitamin B12 deficits, which are prevalent in pregnant women, the elderly, and vegetarians. Active vitamin B12, which is essential for many body processes, including the synthesis of red blood cells and neurological function, is known to be present in several seaweed species, such as purple laver. Seaweeds are rich in essential nutrients like proteins, amino acids, polyunsaturated fatty acids, vitamins, minerals, and polyphenols, all of which contribute to overall health. They provide essential amino acids, beneficial fatty acids for cardiovascular and brain health, and important minerals like iodine, calcium, iron, and magnesium for thyroid health and general well-being. The polysaccharides in seaweed, such as alginate and carrageenan, offer functional benefits, while their polyphenols provide antioxidant and anti-inflammatory properties. Despite these health benefits, seaweeds are underutilized in the food industry. Fortifying products like crackers and biscuits with seaweed could help address nutritional deficiencies, especially vitamin B12. Overall, seaweed has great potential as a sustainable food source that can improve nutrition and prevent diseases.

Keywords: Cobalamin, Functional food, Macroalgae, Nutrition, Seaweed, Vitamin B12 deficiency

1. Introduction

A valuable renewable marine resource, seaweeds flourish in shallow seas with sufficient substrate. They are especially prevalent around the northeast and northwest coasts of our nation. The only sources of agar, alginate, and carrageenan—all of which are utilized extensively in the food, confectionery, and textile industries as thickening, stabilizing, and gelling agents—are seaweeds. Macroalgae, or seaweeds, are larger and have a different structure from microalgae, which are small and primarily unicellular [1]. Between 25,000 and 30,000 different kinds of seaweeds can be found, and they frequently inhabit harsh and complex habitats [2]. All around the world, people eat different kinds of edible algae. Purple laver (Porphyra sp.) and dried green laver (Enteromorpha sp.) are the two most often consumed edible algae.

High amounts of vitamin B12 are present in both (about 32.3 µg/100 g dry weight and 63.6 µg/100 g dry weight, respectively) [3]. The risk of vitamin B12 insufficiency is increased for strict vegetarians since they consume fewer foods from animal sources [4]. Although sea vegetables and edible algae are popular in East Asian cuisines, their use as vegetarian alternatives to vitamin B12 is debatable because some of them include inactive analogues. However, it has been discovered that purple laver (Neopyropia sp.), which is used for producing nori, has actual vitamin B12 in quantities of up to 2.4 µg, which is sufficient to meet the Recommended Daily Intake (RDI) [5]. Vegetarians and those who are vitamin B12 deficient are recommended to take supplements. Nutraceuticals made from natural sources such as seaweed, especially Ulva Lactuca, are one way to obtain vitamin B12 [4]. Seaweed-based diets have shown promise in reducing the risks of several illnesses, including nutritional deficiencies, due to their low calorie content and high content of polysaccharides, minerals, dietary fibre, vitamins, and bioactive metabolites. Edible seaweeds are packed with and sustainable in micronutrients, including vitamins A, B9, B2, B3, B12, B6, B1, B5, E, C, D; polyphenols; sterols; pigments (like fucoxanthins, phycobilins , chlorophylls, and astaxanthin); minerals (like Fe, I, Se, and Zn); and polyphenols [2]. Vitamin B12 deficiency is quite common. In less developed nations, 40% to 80% of people suffer from vitamin B12 insufficiency. About 20% of people over 60 and 6% of people under 60 in the US and the UK are deficient. Despite being so common, B12 deficiency often goes misdiagnosed and can manifest in patients in inconspicuous ways [6]. Foods made from seaweed, frequently referred to as "nutraceutical foods", have numerous health benefits; they are additionally known to have anticancer effects, especially against breast cancer [7]. Infertility, hyperhomocysteinemia-induced thrombosis, megaloblastic anemia, growth as well as developmental disorders in children, hypercellular severe hematological, dysplastic bone marrow, and neurological syndromes that can be lethal are all associated with vitamin B12 deficiency [8]. Food fortification is an economical approach with shown social, economic, and health advantages. With seaweed's nutritional advantages and the growing desire for nutrient-dense meals, fortifying foods like crackers, cookies, and crisps with seaweed to raise their vitamin B12 level is a novel approach with a lot of promise. To retain both nutritional content and sensory appeal, this procedure must be maximised by balancing element ratios, fortification strategies, and processing techniques. This review aims to investigate the many aspects of vitamin B12 fortification in foods made from seaweed.

2. Vitamin B12 And Its Role In Metabolism

Vitamin B12 (molecular weight: 1355.4) forms part of a group of compounds referred to as 'corrinoids,' which are characterized by a corrin macrocycle structure. The term "vitamin B12" is used in the present study to refer to all potentially physiologically active cobalamins, but it is usually limited to cyanocobalamin, the most chemically complex of them. Dorothy Hodgkin's revolutionary X-ray crystallography revealed that the vitamin was amidated, cyanolated, and contained cobalt that contained tetrapyrrole. It was subsequently named cyanocobalamin [11]. Most human dietary supplements contain cyanocobalamin, which is easily transformed into the coenzyme forms of cobalamin [3]. Malabsorption is the primary cause of vitamin B12 insufficiency, despite the fact that nutritional inadequacy is common among the ovo-lacto vegetarians, elderly and vegans with insufficient diets. Other contributory variables may include atrophic gastritis, disease-related interference with ileal absorption of vitamin B12, drug-nutrient interactions, bacterial overgrowth-induced resection or interference, inadequate IF synthesis, and a few less common genetic disorders. Also, people who are vegans are more likely to have vitamin B12 deficiency but satisfy their vitamin B12 needs with fortified foods or medication [10]. There are four phases of low vitamin B12 levels. Depletion can be seen by the first two stages, while deficiency can be seen by the second two. Low serum vitamin B12 is stage I; low cell reserves are stage II; biochemical deficit is stage III; and clinical deficiency with obvious symptoms is stage IV. Clinical and subclinical types of vitamin B12 deficiency are differentiated by other categories [11]. It should be mentioned that while gut microbes can produce vitamin B12, they do not offer humans substantial sources of cobalamin for several reasons. One of these is that the total amount of cobalamin in faeces only amounts to 2% of the entire amount needed because it is mainly produced within the colon, which lies downstream of the ileum and makes absorption unlikely [8]. The biliary cobalamin can be reabsorbed to release the vitamin B12 stored in the liver. The liver stores roughly 2–5 mg of vitamin B12 however, humans require 1–4 µg daily. Vitamin B12 deficiency is therefore persistent and occasionally irreversible, with symptoms usually appearing three to five years after malabsorption first takes place. Increased oxidative stress is also associated with vitamin B12 deficiency, though the precise mechanism is still unclear. The absence of vitamin B12's scavenging activity may result in increased oxidative stress. This increased stress can change cobalamin's oxidation state, which can affect its metabolism and aggravate the insufficiency [8]. Megaloblastic anemia and neuropathy are the two major indications of vitamin B12 deficiency [3]. Compared to those who eat animal products, vitamin B12 insufficiency is more common among people who eat plant-based diets, especially vegans as well as lacto-ovo vegetarians. One significant source of it is the green algae Chlorella, that has cobalamin. The most popular edible algae, purple laver, green laver, and macroalgae (seaweeds), are the finest non-animal sources of cobalamin. In the United States, 2.4 µg is the recommended daily consumption. which helps prevent vitamin B12 deficiency, might be met by roughly four grams of dried purple laver [11].

3. Seaweeds and it's Types

The ocean's producers—plants that possess chlorophyll—provide nourishment for its inhabitants. The seaweed (algae), which range across scales from microscopic to macroscopic (multicellular), is one of these significant producing groups [12]. Seaweeds are technically members of the algae, a vaguely defined group of plants. Despite having no taxonomic meaning, the term "seaweed" is frequently used to refer to large attached (benthic) marine algae that are members of the Rhodophyceae, Chlorophyceae, and Phaeophyceae families, which stand for red, green, and brown algae, respectively. In contrast to higher plants, algae lack actual roots, stems, and leaves. Nonetheless, some of the bigger species, which serve as the foundation for most industries, have attachment organs, or hold-fasts, that resemble roots. Furthermore, some species may have a stipe, which is a stem-like element that flattens out into a broad lamina or leaf-like portion [13]. The absence of specialized features distinguishes seaweeds, also known as marine macroalgae, from plants. They are sessile, multicellular, photosynthetic eukaryotes. Although field growing of some economically viable seaweeds has been attempted, seaweed production in India is still in its experimental stage. India's seaweed flora is exceptionally varied. Including forms and variants, 1153 species and 271 genera of marine algae have been identified from Indian seas. 844 species, spread among 217 genera, have been identified in the most recent systematic account. Pheophyta (191 species), Chlorophyta (216 species), Xanthophyta (3 species), and Rhodophyta (434 species) are the most prominent of these. Tamil Nadu has recorded the most species (302) of them, followed by Gujarat (202) Maharashtra (159), Lakshadweep (89), Andhra Pradesh (79), and Goa (75) [12]. Seaweeds can be categorized into three major categories based on their pigmentation: brown, red, and green. Phaeophyceae, Rhodophyceae, and Chlorophyceae are the names given by botanists to three broad groups, respectively.

Brown algae are a broad category of multicellular algae that belong to the Phaeophyceae class. The Phaeophyceae class includes the vast group of multicellular algae known as brown algae. Enormous kelp, which can often be 20 meters long; thick seaweeds that imitate leather that are 2 to 4 meters long; and smaller species, which are 30 to 60 centimeters long, are among their many sizes [1]. They are only seen in marine forms. The brown algae is thought to be the seaweed species that grows the fastest worldwide. The hues of brown algae range from deep brown to olive-yellow. Fuxoxanthin, a photosynthetic pigment, and the accessory carotenoid pigment are responsible for the coloration. The brown algae also include xanthophylls, chlorophyll a and c, and other photosynthetic pigments [12]. Warmer waters are home to brown seaweeds, although they are rarely used as food and are less effective in producing alginate. In brown seaweeds, the genera Laminaria, Undaria, and Hizikia are the main sources of food. Wild seaweed harvests were the sole source at first, but with the advent of cultural methods, seaweed for food now mostly comes from farming rather than natural sources. Cold waters like Nova Scotia, Canada; more moderate waters like Morocco's beaches; and tropical oceans like Indonesia are all home to red seaweeds [1]. Though they are not always red, red seaweeds are often smaller, with a typical length of a few centimeters to a meter. They can occasionally be brownish or purple. Chlorophyll is what gives the green algae their green color. To survive, they require adequate sunshine, which is only available in shallow seas. Green algae are therefore seen at the sea's borders close to land [12].

Figure 1 Representing the Classification and Distribution of Seaweed

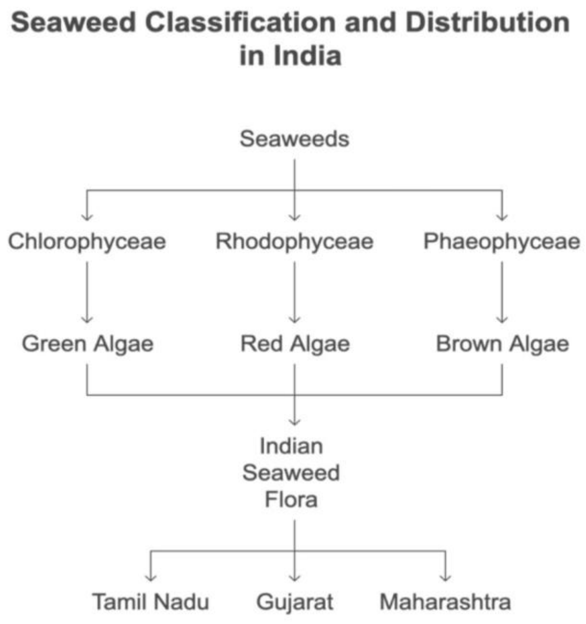
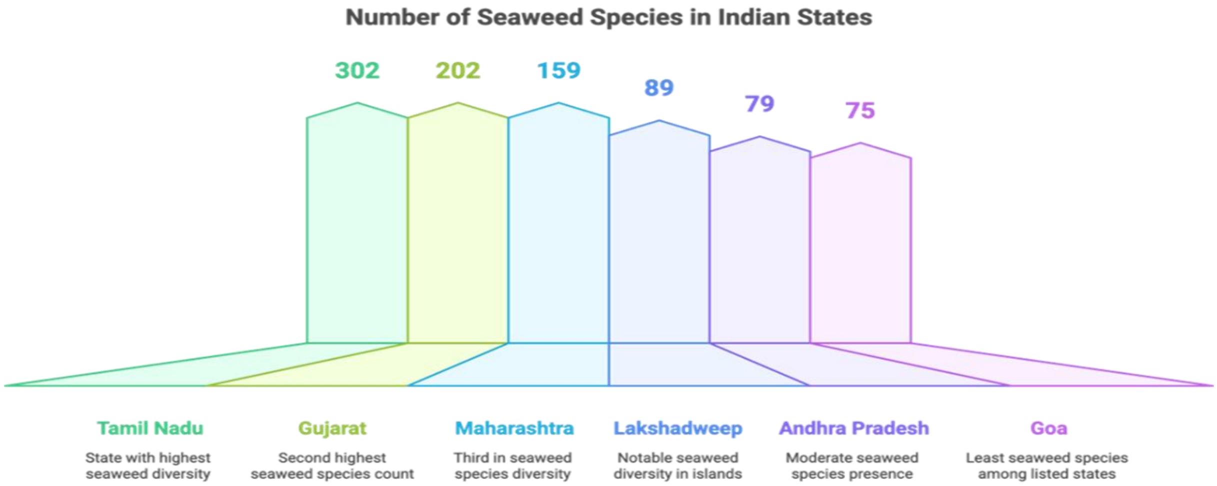


Figure 2 Representing the Number of Seaweed Species in Indian States



4. Nutritional Composition Of Seaweed

Seaweeds are a broad and common array of organisms with photosynthesis that are crucial to aquatic environments and to the wellness of humans [14]. Seaweed's biomass and extracts comprise bioactive chemicals that hold valuable biological properties and could potentially be used in pharmaceutical and nutraceutical applications [2]. From a nutritional perspective, seaweeds are a great source of carbohydrates, unsaturated fatty acids, phenolic elements, proteins, vitamins, and minerals. Species, age, size, and reproductive stage, as well as environmental parameters including the pH level, depth, salinity, temperature, levels of oxygen, UV radiation, and light intensity in the surrounding seawater, may all affect the nutritional makeup of seaweeds [15].

4.1 Proteins And Amino Acids

Large macromolecules called proteins are made up of multiple lengthy chains of residues from amino acids. Microalgae and seaweed are regarded as valuable sources of protein. Some species of seaweed and microalgae have protein contents that are similar to those of traditional protein sources, including meat, soybeans, eggs, and milk [16]. All of the EAA, including histidine, methionine, leucine, and lysine, which humans are unable to synthesize and must acquire from food, have been identified in a large number of seaweed species at proportions that are usually higher than 30–40% of their protein composition [2]. Red and green algae, such as Porphyra spp., Pyropia spp., Palmaria palmata, and Ulva spp., are examples of aquatic macroalgae that often have higher protein content (as a percentage of dry weight) than most kinds of brown algae [17]. In instance, aspartic acid (8–13% of protein) as well as glutamic acid (9.5–19% of protein) are abundant in seaweeds, along with significant levels of glycine and alanine. Valine is one of the essential amino acids (EAA) found in them. According to studies, the red seaweed Porphyra tenera (Nori) has a protein content that varies between 33% and 47% of its dry weight, whereas the protein content of Palmaria palmata (dulse) ranges from 6% to 35% of its dry weight [2]. The umami flavour of seaweeds was also discovered to be closely associated with three prevalent amino acids identified in seaweed proteins: aspartic acid, glutamic acid, along with alanine. The possibility of obtaining seaweed protein to be utilized as a taste enhancer was brought to light by this discovery [15]. Glycine, arginine, alanine, and glutamic acid are especially prevalent in algae proteins, which additionally offer crucial amino acids in amounts that correspond to the FAO/WHO recommended values. However, the most limited amino acids in algal proteins are cystine and lysine.

4.2 Fatty Acids And Sterols

Polyunsaturated fatty acids (PUFAs) are abundant in macroalgae, primarily DHA and EPA. Since they are closely linked to significant biological benefits like cardiovascular protection, anti-inflammatory, and anticancer properties, EPA and DHA have been identified as the two most significant PUFAs of marine lipids [18]. Brown, red, and green seaweeds have lipid concentrations that fall between 0.1 and 11.5%, 0.4 and 12%, and 0.2 and 15% of their dry weight, correspondingly. PUFAs, which frequently occur as omega-6 and omega-3 lipids, make up a significant amount of these lipid concentrations [15]. ALA (α-linolenic acid) and LA (linoleic acid) are two essential fatty acids found in seaweeds that humans are unable to synthesize and must and should acquire through diet. Additionally, seaweeds have balanced ω3 and ω6 PUFA contents, which increases their usefulness as a component of a balanced diet [2]. Several compounds have been found in seaweed lipids, notably 20:4 n-6 ARA (arachidonic acid), 18:2 n-6 LNA (Linoleic acid), 22:6 n-3 DHA (Docosahexaenoic), 20:5 n-3 EPA (eicosapentaenoic), and 18:3 n-3 ALA [15]. Previous studies have shown the potential benefits of seaweed-derived DHA (docosahexaenoic acid), ARA (arachidonic acid), and EPA (eicosapentaenoic acid) for cardiovascular disease prevention, inflammatory disease modulation, and brain health [2, 15]. Notable market examples include drinks that contain bioactive peptides like Calpis or Evolus, which can be consumed to meet the requirements, and additional foods supplemented with algae-derived omega-3 polyunsaturated fatty acids [19]. Consistently consuming 10 g of seaweed, as evaluated in their study, could positively affect human health by including the right kinds of proteins, fiber, and fatty acids. According to Skrzpczyk et al [20]. Neutral and glycolipids are the most prevalent lipids in the modest (1–5%) lipid algae concentration. In general, brown algae have lower levels of EPA but higher levels of oleic acid, LNA, and ALA, while red algae have higher levels of EPA, palmitic acid, oleic acid, and ARA. Green algae have higher levels of LNA, ALA, palmitic acid, oleic acid, and DHA. Omega-3 and omega-6 fatty acids are commonly found in both red and brown algae [21]. The overall quantity of sterols and different kinds of sterols that exist in algae varies. Numerous algae, notably red and brown macroalgae, contain fucosterol, a substance that may be beneficial for treating the challenges of high blood pressure and diabetes as well as other major health problems [17]. The anti-inflammatory, anti-aging, anti-obesity, anti-Alzheimer's, antibacterial, antifungal, anti-ulcer, and anti-cancer activities of seaweed extract rich in phytosterols have been shown in vitro. Phytosterols have been recognised as essential elements of a nutritious diet that have a capacity to lower cholesterol. They may lower blood levels of LDL and total cholesterol as well as lower the risk of developing different kinds of cancer [2].

4.3 Carbohydrates

Essential macronutrients, carbohydrates are mainly in charge of supplying the energy required to sustain physical activity and maintain body functioning. An excellent method to get carbohydrates is by consuming seaweed. The United States Department of Agriculture's most recent SR Legacy data indicates that edible seaweeds contain about 81% carbohydrate by dry weight; depending on their dry weight, red, green, and brown seaweeds have carbohydrate contents ranging from 8.3% to 68.2%, 4% to 79.9%, and 12.8% to 81%, respectively. The molecular structure of carbohydrates can be classified as either polysaccharide, oligosaccharide, disaccharide, or monosaccharide [15]. Ascophyllum, Porphyra, and Palmaria had the greatest concentrations of total polysaccharides in macroalgae, which varied between 4 and 76% of dry weight. Other green species, including Ulva, displayed levels as high as 65% on a dry weight basis. Among the seaweed polysaccharides are pertinent bioactive compounds such as laminarin, fucoidan, carrageenan, and alginate. Other phycocolloids from macroalgae, including agar, are also often used in the food and animal feed industries as stabilizers, thickeners, and emulsifiers [19]. While brown seaweeds mostly contain fucoidans, alginates, and laminarins, red seaweeds are rich in essential polysaccharides such as carrageenans and agars [15]. Seaweed has a fairly substantial polysaccharide content, although it is not very digestible [2]. Amongst the seaweed polysaccharides are pertinent bioactive compounds such as laminarin, fucoidan, carrageenan, and alginate. Alginates consist of β-D-mannuronic acid (M) as well as α-L-guluronic acid (G) units joined by one to four glycosidic bonds, forming linear, unbranched polysaccharides. The D-galactosyl residues (D- and G units) that make up carrageenans are sulfated linear galactans joined alternatively by β-1,4 and α-1,3 glycosidic linkages. Brown macroalgae include cell wall polysaccharides called fucoidans, which are crucial in shielding macroalgae from environmental stresses. The energy-storing polymer family known as laminarins is made up of β-D-glucose monosaccharides joined by β-1,3 bonds, with different branching at β-1,6 [19]. However, because they contain a high percentage of soluble dietary fiber (between 55 and 70 percent), they are not an excellent source of carbohydrates in terms of absorption. Furthermore, the main low molecular weight carbohydrate present in many brown algae species, especially Laminaria and Ecklonia, is mannitol. Both Laminaria hyperborea and Ascophyllum nodosum contain less than 10% mannitol by dry weight. Finally, seaweeds contain between 20% and 70% of carbohydrates, combining structural, storage, and functional polysaccharides. However, in terms of absorption, they are not a great source of carbohydrates due to their high soluble dietary fiber content (in the range of 55 and 70%) [21].

4.4 Vitamins

Vitamins serve as crucial micronutrients that maintain the health and vitality of living things. Vitamins fall into two major categories: water-soluble and fat-soluble, into which vitamins can be divided based on their solubilities According to studies, seaweeds contain fat-soluble vitamins like K, vitamin A, vitamin D, and vitamin E, as well as water-soluble vitamins like different types of vitamin B and vitamin C [5, 21]. Vitamins are abundant in algae-based food items. The vitamin C content of several sea vegetables, including sea spaghetti (Himanthalia elongata), laver (Porphyra umbilicalis), and Gracilaria changii, is similar to that of common vegetables like tomatoes alongside lettuce. The vitamin C content of mandarin oranges and the brown seaweed Eisenia arborea is similar. Sea vegetables are also an excellent source of B-group vitamins, including B1, B12, and the lipophilic vitamins A along with E (tocopherol). The level of α-tocopherol, the type of vitamin E that is most physiologically active, in kelp (Macrocystis pyrifera) is similar to that of plant oils that are high in this vitamin, including sunflower, soybean, and palm seed oils. Furthermore, the seaweeds Gracilaria chilensis and carrots may not have as much β-carotene as Codium fragile [17]. In this sense, algae are a great source of folic acid, riboflavin, pantothenic acid, niacin and the vitamins A, B1, B12, C, D, and E. Algae also include B-group vitamins, including B1 and B12, and the lipophilic vitamins A and E. Last but not least, seaweed products are among the few vegetarian ways to receive cobalamin [21]. While seaweeds have been found to contain a variety of vitamins, it cannot be regarded as a good source of vitamins B9, B6, B8, B5, or E. Interestingly, however, high levels of vitamin B12 were found in many species, including Ulva lactuca, Fucus vesiculosus , and Pylaiella littoralis. Although vitamin B12 was previously solely found in animal-based diets, its discovery in seaweeds was considered a milestone because it is crucial for human brain processes [15]. Around the globe, consumers eat a variety of edible algae, though dried green and purple laver are among the most prevalent. These algae have about 63.6 µg/100 g and 32.3 µg/100 g of dry weight, respectively, making them great sources of vitamin B12 [3]. Only prokaryotes can synthesize cobalamin, and it has been demonstrated that bacteria that produce B12 are either found on the surfaces of eukaryotic algae or are closely related to them. Up to approximately 0.06 mg of vitamin B12 (100 g)−1 algal dry weight is present in Pyropia yezoensis (nori), which is equivalent to the amount in beef liver [17].

4.5 Minerals

The body requires minerals as essential micronutrients to maintain cell function and metabolism. Seaweeds can absorb a wide range of minerals because they are a plentiful source of minerals owing to their coastal habitat. Minerals can make up as much as 30% of the dry weight of seaweeds [15]. Because of their current mineral content, which is up to 100 times higher than that of vegetables, seaweeds have been employed as a source of minerals for feed and dietary supplements [2]. Prior research has identified the minerals found in seaweed, such as K, Mg, Zn, Ca, I , Cu, Na, Ca, and P. Among these elements, it was discovered that seaweeds have larger concentrations of sodium, calcium, potassium, magnesium, and copper than meals found on land [15]. Because seaweed species are high in minerals and trace elements, they are useful food additives. For trace elements like zinc, iron, manganese, and copper, as well as macro elements like Na, K, Ca, and Mg, they can assist in meeting RDI [2, 21]. However, the taxonomic group, geographic location, sea sodium, physiological differences, and even the type of processing and mineralization technology used can all affect the mineral composition [21].

4.6 Iodine

Human use of seaweed has long been associated with a lower incidence of goitre and other thyroid conditions. Hypothyroidism results from iodine insufficiency, but hyperthyroidism or hypothyroidism can be brought on by excessive iodine intake. While seaweeds are a great source of iodine, especially in areas with limited access to other food sources, their iodine content varies greatly depending upon species, preparation techniques (given that many iodine compounds tend to be water-soluble), and storage time (because iodine may evaporate in humid conditions) [2, 17]. Brown seaweeds typically contain higher iodine levels compared to green (Ulva spp., which have 2.0–25 mg/100 g dry weight) and red (Palmaria spp., with 10–100 mg/100 g dry weight) seaweeds. For instance, brown seaweeds like Laminaria and Saccharina have iodine concentrations exceeding 1200 mg/100 g dry weight. The genus Laminaria has some of the most potent iodine accumulators of any biological system. Laminaria digitata has been used as a food and medicine for more than 1500 years in Japan, China, and Korea. It has been used to cure goiter and myxedema. Likewise, Laminaria japonica has long been used as a dietary iodine source to prevent goiter in China [2]. Iodine is abundant in certain kelps (Laminaria spp., Saccharina spp.), and kelp powder is a commercially available source of this essential ingredient in salts. Similar to the iodine content of Palmaria palmata (dulse), a red sea vegetable, other brown algae, including Undaria (wakame) and Alaria (Atlantic wakame), have comparatively low iodine contents. However, because other brown macroalgae have high iodine content, there is serious concern that consuming too much of these specific sea vegetables may be harmful [17].

4.7 Pigments

In addition to sea algae, all living organisms exhibit natural colours, including fungi, mammals, and invertebrates. However, non-animal natural pigments may be found in marine algae. The Phaeophyceae, Rhodophyceae, and Chlorophyceae are the names of the brown, the red, and green marine algae, respectively, based on the natural pigment concentration of the algae. Marine algae have three fundamental groups of natural pigments: phycobiliproteins, carotenoids, and chlorophyll [22]. Carotenoids and chlorophylls are the major pigments present in seaweeds, and autotrophs use them for absorption of sun energy for photosynthesis. Brown seaweeds are distinguished by their principal xanthophyll, fucoxanthin; red seaweeds are distinguished by the abundance of chlorophyll a and b; and green seaweeds are distinguished by the presence of most PBPs, including phycoerythrin. Green seaweeds are mostly composed of the carotenoids violaxanthin, β-carotene, neoxanthin, lutein, and zeaxanthin. Zeaxanthin, lutein, and α- and β-carotene are frequently found in red seaweeds. The carotenoids violaxanthin, fucoxanthin, and β-carotene are commonly found in brown seaweeds. In the food business, chlorophylls and their derivatives are mostly used as natural food and beverage colourants [2,21] . All seaweeds include the natural pigment chlorophyll, which is greenish and lipid-soluble with a porphyrin ring. Seaweeds have four different forms of chlorophyll, having chlorophyll a being probably the most significant. In addition, chlorophyll b as well as have been identified. Chlorophyll is the most prevalent tetrapyrrolic pigment found in seaweeds. The pigment chlorophyll a is blue-green in colour. Only green algae contain chlorophyll b, the second most significant type of chlorophyll. The pigment chlorophyll b is green or yellow in hue. Brown seaweeds contain chlorophyll c. There are three types of chlorophyll c: c1, c2, and c3. However, only chlorophyll c 1 along with c 2 are found in seaweeds. The pigment chlorophyll c has a blue-greenish hue [23]. Certain carotenoids are also categorised as vitamins based on their chemical and biological action rather than just their structure. They are hormones, antioxidants, cell signalling mediators, and regulators of the growth and differentiation of cells and tissues.

4.8 Polyphenols

The main category of phytochemicals found in the diet of humans, polyphenols are a diverse collection of substances that can be present; the main application for chlorophylls and their derivatives has been as natural colorants in meals and drinks that contain essential oils, fruits and vegetables, and seeds [24]. In recent years, polyphenols have become more well-known for their potential in pharmaceutical and cosmetic applications, primarily because of their anti-cancer, anti-inflammatory, anti-diabetic, and antioxidant qualities. They are also known to prevent autoimmune disorders, arthritis, and cardiovascular diseases by shielding tissues from oxidative stress [2]. HJJ Polyphenols are found in relatively small amounts in algae, with brown algae usually having higher concentrations than green and red algae. (<1% dry weight), but Ascophyllum and Fucus algae can have up to 14% dry weight. Phenoltannins, which are produced through the oligomeric structure of phloroglucinol (1,3,5-trihydroxybenzene), are the most often recorded polyphenols discovered in brown algae, especially in species of the genus Ecklonia. Phlorotannins are present in Ascophyllum nodosum, Fucus vesiculosus, Sargassum spinuligerum, and Cystophora retroflexa at levels ranging from 20 to 250 mg/g dry weight [21]. Polyphenolic substances, including catechins, flavanols, and phlorotannin, are abundant in marine macroalgae. Bromophenol, flavonoids, and phenolic acids make up the majority of the phenolic chemicals found in red and green algae. However, the predominant polyphenolic secondary metabolites that are exclusive to marine brown algae are phlorotannins, which are a class of complex polymers of phloroglucinol (1,3,5-trihydroxybenzene) [24]. The primary phenolic compounds found in brown seaweeds (like Fucus vesiculosus, Ascophyllum nodosum, Saccharina latissima, and others) are phenolotannins. In contrast, green (Ulva sp.) and red (Asparagopsis armata, Pterocladiella capillacea, and Porphyra umbilicalis) seaweeds contain other phenolic compounds, such as flavonoids and bromophenols.

5. Inclusion of Seaweed in Food Industry

The food industry is interested in seaweeds because they are renewable sources of high-value chemicals. By incorporating them into baked goods, dairy products, fish, meat, or vegetable-based items, new functional food products can be created, enhancing their nutritional value, quality, and positive health effects [21]. For a very long time, seaweeds have been utilized as food in many forms. An estimated 100,000 tons of seaweed are consumed each year in Japan alone under the names of various items like wakame, kombu (konbu), and nori. Additionally, seaweeds are used to make seaweed jams, seaweed salad, seaweed masala, pickles, seaweed wafers, seaweed porridge, and seaweed jelly [12]. Food products are made better and have longer shelf lives because of seaweed isolates, especially polysaccharides. The most prevalent seaweed polysaccharide isolates are carrageenan, agarose, alginate, and agar [20]. Agar, also referred to as "vegetable gelatin", is found in Gelidium and Gracilaria species. This chemical, used to manufacture fruit sweets and jellies, requires no potassium or calcium salts to form a stiff gel at room temperature water, even at low concentrations [21]. Compared to agar, carrageenan is a much preferable stabiliser and emulsifier in food. The three primary classes of carrageenan employed in commercial applications are kappa, lota, and lambda. Because of their thickening and suspending qualities, the κ and ι forms of carrageenan are primarily used in milk-based goods, including chocolate, ice cream, dessert gels, and evaporated milk [20]. Seaweeds were also found to have beneficial benefits on poultry products. The red seaweed Kappaphycus alvarezii was used as an antioxidant to boost redness and reduce lipid oxidation in mechanically deboned chicken meat sausages. Furthermore, cured turkey meat sausages produced by the brown algae Treptacantha barbata (previously Cystoseira barbata) demonstrated resistance to oxidation [21]. One affordable strategy that could help combat malnutrition worldwide is food fortification. Research on food fortification has demonstrated benefits on social, economic, and environmental levels in addition to controlling and preventing micronutrient deficiencies in vulnerable groups, particularly women and children [9]. Although they are not always readily available, a number of imported seaweed snacks, including chips, fermented seaweed salad, and roasted seaweed snacks, can be found at some superstores in Bangladesh [2]. One of the most widely consumed foods is bread and bakery goods, which offer a great deal of opportunity for supplying marine beneficial elements. Bread was made stiffer without sacrificing quality by adding red seaweed Kappaphycus alvarezii powder (2–8%). The phytochemical content of breadsticks was enhanced by H. elongata, with 17.07% incorporation indicating increased antioxidants and fiber. M. myagroides extract (0.5%) enhanced the overall quality, microbiological stability, and shelf life of bread, delivering beneficial components from the sea [25]. Seaweeds are abundant in sulfated polysaccharides that interact with various textures as well as cellular proteins to produce their bioactivity. Seaweed utilized as functional food should be explored globally to enhance immune responses, according to several toxicological tests and clinical studies [26]. Seaweed, which used to be a staple of the Irish cuisine, is currently gaining popularity. More and more people are reading recipe books that advocate using "sea vegetables" or "marine vegetables" in home cooking. The usage of seaweed in food items is growing, and as consumer health and nutrition become more popular in the food industry, product development for salads and wraps appears to be progressively shifting [27]. Additionally, seaweeds have been included into cereal-based goods such breadsticks, cereal bars, and semi-sweet biscuits. Due to their lower fat and sugar content, semi-sweet biscuits are a better alternative to cookies. At 1.0%, 5.0%, and 10%, the green seaweed Caulerpa racemosa has been utilised in place of refined flour in these biscuits. Along with improving the flour-seaweed mix's ability to absorb water and oil, the results also improved its nutritional value (fibre, protein, and phenolic content) and antioxidant value [20,21]. The name "umami" was developed because of the unique and fascinating flavour of the amino acids glutamic acid and aspartic acid, which are particularly abundant in a number of seaweed species. Monosodium glutamate, a flavour enhancer that was first discovered in the brown seaweed L. japonica (kombu), has been shown to be particularly attractive to the umami taste sensation [16, 21].

Table 1 An Overview of the Studies on the Value Added Food from Seaweeds

SEAWEED	INCORPORATED FOOD	TYPE OF EFFECT	REFERANCE
Ulva Lactuca (30%)	Biscuits	A substantial protein content, a favourable amino acid profile, and an enhanced mean anthropometric profile in kids	[28]
U. pinnatifida(10%)	Pasta	Elevated antioxidant activity	[16]
Himanathalia elongate, Laminaria ochroleuca, Porphyra umbilicalis, Ulva lactuca and Undaria pinnatifida	Hard cheese	Rise in overall phenolic compounds and activity as antioxidants, elevated potential to retain moisture, and decreased its pH level.	[20]
Cladophora spp. Ulva spp.(5.0, 7.5, or 2.5% (depending upon wheat flour))	Bread	Content increases for protein and fibre; minor modifications to technical and sensory aspects	[21]

Eucheuma cottonii (2.5-7%)	Mille crepes cake	Greater levels of fibre	[29]
U. reticulata	Seaweed chocolate	Significant increases in haemoglobin, overall iron binding ability, mean corpuscular haemoglobin, mean corpuscular volume, serum iron, and serum ferritin levels were seen in the examined patients; high iron content with improved bioavailability compared to control.	[30]
Sargassum wightii (3-5%)	Fish jerky	Better levels of fibre, carbohydrates, and minerals (ash); higher levels of phenolic content and DPPH radical scavenging activity	[31]
Ulva lactuca Spp	Beverage	Elevated total solube soild content, decreased acidity, Minimal alterations to the raw seaweed juice's calcium, phosphorus, and iron concentrations over time, a minor variation in the amount of sugar overall	[32]
Kappaphycus alvarezii	Fish sausage, flat rice noodle, and yellow alkaline noodle	The total phenolic content, fibre and ash contents significantly increased, the moisture contents also increased,	[33]
Ascophyllum Nodosum, Fucus vesiculosus, Bifurcaria bifurcata (500 ppm)	Pork liver pâté	Significantly higher protein concentration; optimal colour characteristics; comparable level of oxidation protection to synthetic antioxidants; reduced levels of volatile chemicals overall.	[21]
Palmaria palmata or Saccharina longicruris	Camembert-type cheese	Appropriate bioactivity development during the storage time	[34]
Enteromorpha	Pakoda	An increase in seaweed content improved the amounts of calcium, iron, protein, ash, and total dietary fibre. Seaweed was added, which decreased the overall phenol concentration and	[25]

		free radical-scavenging activity while increasing the reducing power.	

6. Conclusion

To sum up, seaweeds are a valuable and replenishable marine resource that has enormous potential for use in a variety of sectors, especially along the southeast and northwest coasts of nations like India. The abundance of bioactive substances found in seaweeds, including vitamins, minerals, polysaccharides, and antioxidants, makes them valuable to the food, medicine, and cosmetic industries. Seaweed products such as agar, alginate, and carrageenan are employed as stabilising agents, illustrating their numerous industrial applications. Additionally, because seaweeds have health benefits and can enhance the nutritional profile of foods, they have become a desirable alternative in response to the growing demand for functional foods worldwide. Vitamin B12, a vital component frequently lacking in vegetarian and vegan diets, is found in seaweeds, especially species like purple laver (*Porphyra sp*.) and green laver (*Enteromorpha sp*.). Using seaweed as a natural supply of B12 in food products could help fill these nutritional gaps, especially as B12 insufficiency is becoming more common worldwide, especially among vegetarians. Additionally, seaweeds offer a variety of health advantages, including lowering the risk of diabetes, heart disease, and nutritional deficiencies. An unique method of enhancing human health is their incorporation into foods like crackers, biscuits, and crisps by fortifying them with vitamin B12. Seaweed-based foods are being used in many culinary applications due to growing global awareness of their health advantages, particularly in East Asian countries where they have long been consumed. Given their lack of need for fertilisers, fresh water, or arable land, seaweeds present an environmentally beneficial solution to the growing demand for wholesome and sustainable substitutes. They are therefore a desirable resource for supplying the world's population's nutritional needs, especially in areas where it is difficult to produce enough animal-based sources of vitamin B12.. Seaweeds continue to be underutilized in food products despite their advantages. In order to maximise their potential, efforts should be focused on integrating seaweed into food compositions in a way that balances processing methods, nutritional content, and sensory appeal. Given its expanding importance in addressing vitamin deficiencies, boosting diets, and promoting people's health and well-being globally, seaweed-based nutraceutical foods appear to have a bright future.

7. Author's Biography

Shradha Singh As a final-year M.Sc. candidate in Food Science and Technology at Babasaheb Bhimrao Ambedkar University (A Central University), Lucknow, I bring a strong academic foundation in food chemistry, microbiology, and advanced food processing technologies. My passion lies in driving innovation at the intersection of food quality, safety, and sustainability. I am particularly interested in exploring functional foods, modern preservation techniques, and the regulatory frameworks that shape food production. Through the integration of classical food science and emerging technologies, I aim to contribute to the development of more efficient, sustainable, and health-focused food systems—bridging the gap between academic research and real-world application.

Dr. Priyanka Shankar is an assistant professor at Babasaheb Bhimrao Ambedkar University (A Central University) in Lucknow. She specializes in Food and Nutrition and has an extensive academic and research background. She made major contributions to the discipline through papers, conferences, and academic collaborations. Dr. Shankar's work is to promote research and innovation, guide academics, and advance scientific understanding.

Dr. Anu Ram Kailash Mishra is a famous academic and resource person at Babasaheb Bhimrao Ambedkar University (A Central University) in Lucknow. With a background in Food and Nutrition, her research focuses on human nutrition, functional foods, and food safety. Her contributions to the discipline include scholarly articles, conference presentations, and academic projects. Dr. Mishra is devoted to improving nutrition science research and promoting evidence-based approaches to health and food sustainability.

Ayushi Singh is a junior research fellow at Babasaheb Bhimrao Ambedkar University (A Central University) in Lucknow. With a strong interest in Food and Nutrition, she is committed to investigating novel ways to important difficulties in the subject. She has worked as a dietician at Sri Ganga Ram, Hospital. She pursues her intellectual endeavors with a strong commitment to excellence and a clear ambition to make meaningful contributions to the academic world.

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