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Review article

# Seaweed: Nutritional and gastronomic perspective. A review

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ABSTRACT

Seaweed are organisms rich in many bioactive compounds such as proteins, minerals, vitamins, fibers, essential amino acids, pigments, and fatty acids, which give them extraordinary antihypertensive, antidiabetic, antioxidant, anti-inflammatory, antitumoral, antiviral, and antimicrobial properties. Seaweed could potentially contribute to future global security in functional foods and nutraceuticals and could be an important compound in the pharmaceutical and biotechnological industries in drug development, among other uses. This review focuses on the gastronomic point of view and discusses the compositional and nutritional characteristics, topics related to consumption, current applications and technologies, limitations and challenges in production, and market developments in this rising market.

## 1. Introduction

Seaweed are very diverse organisms, highly different in shape, size, and life cycle. They are assembled into three groups: red (Rhodophyta), green (Chlorophyta), and brown (Ochrophyta, Phaeophyceae). Some are adapted to protected areas of the coast, while others grow in exposed areas with the strong action of tides and waves [1]. In addition, they are settled at different depths in fresh or salty water, playing crucial ecological roles in marine communities and being considered ecosystem engineers [2,3]. The three main groups are found in a wide variety of different physical forms, including crusts, and have different filament complexities, from simple to branched.

The bioactive compounds present in these organisms, including pigments, fatty acids, sterols, proteins, lipids, fibers, and polysaccharides, are very important from a nutritional perspective [4], showing positive effects on human health [5–7]. Moreover, seaweed contains several mineral elements (e.g., Na, K, Ca, Mg, Fe, Zn, Mn, and Cu), vitamins [8,9], and low fat and sugar contents [10,11]. Bioactive compounds with high industrial applicability have been reported in macroalgae [12], and multiple applications are being developed (Fig. 1). They have been used in the industrial sector as food, fuel, plastics, and cosmetics [10,14] and in the pharmaceutical industry [6] due to their anti-inflammatory, antimutagenic, antitumor, antidiabetic, and antihypertensive properties [12].

Seaweed has a long history of consumption in coastal areas around the world and is part of the daily diet of many countries [15]. Interest in nutrition and healthy life has increased, and consumers are looking for healthy alternatives as a food source [8]. This growth in seaweed demand has led to the introduction of the term 'phycogastronomy' in the gastronomy sector [16]. Around 600 seaweed species are used worldwide for food, and the most consumed are brown, followed by red and green seaweed [17]. More specifically, in Europe, more than 200 species of macroalgae have nutritional and commercial value, according to the Food and Agriculture Organization of the United Nations (FAO) [18,19].

In relation to the increase in the demand for seaweed and their derivatives for nutrition, it is very important to develop projects and collaborations between interdisciplinary groups to increase knowledge of macroalgae. Nowadays, seaweed represent a growing source of food for humans, and this review aims to provide an updated perspective of the main aspects of seaweed in gastronomy with a precise and actual viewpoint of the nutritional components, bioavailability and possible (biotechnological) applications, weaknesses, and uses. The current review contains key points related to the food sector, focusing on the sources, classification, benefits, and risks for health and cultivation.

## 2. Pigments

Pigments are substances that capture light and transform it into

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energy through photosynthesis. Three types of photosynthetic pigments are found in seaweed: chlorophylls, carotenoids, and phycobilins. Chlorophylls, mainly chlorophyll *a* (Chl a), are essential in photosynthesis. Carotenoids and phycobilins are accessory pigments that conduct energy to Chl *a*. Macroalgae belonging to the same group have some similarities in the pigment profile. The highest chlorophyll quantities are found in green seaweed; brown macrophytes are characterized by their fucoxanthin content, while red ones are known for their phycobilins [20].

Colors are an essential aspect of food, and pigments are responsible for them. In this context, the principal application of pigments is as a natural colorant [21]. In recent years, due to consumer concerns about health, there has been an increasing tendency to use natural pigments [22], as they are considered health promotional ingredients that exhibit highly beneficial functions and are promising alternatives to synthetic components or colorants [21]. In addition, pigments exhibit biological activities with a high potential to benefit human health due to their nutraceutical properties.

### 2.1. Chlorophylls

Chlorophyll is the principal and most widely distributed pigment for the photosynthesis process. They are divided into *a*, *b*, *c*, and *d*. Chl *a* is the primary pigment for photosynthesis, and *b*, *c*, and *d* are the secondary (or accessory) pigments that support the primary pigment [23]. Chlorophylls are responsible for the green color of seaweed and are used as natural colorants in beverages, pasta, soups, etc. [21]. For the legal aspects of green natural colorants, European current legislation [24] allows the use of E-140 and E-141, two natural green colorants obtained from chlorophylls [25]. Among seaweed, Chlorophyta have Chl *a* and *b*, while Ochrophyta have Chl *a* and *c*, and Rhodophyta have Chl *a* and *d* (Table 1) [20,23]. Chlorophyta have the highest total chlorophyll content, followed by Ochrophyta and Rhodophyta [35,36]. However, Othman et al. [37] in their research showed that *Padina pavonica* (Ochrophyta, Phaeophyceae) and *Caulerpa lentillifera* (Chlorophyta) exposed similar values of total chlorophylls, around 7–7.5 μg $g^{-1}$ dry weight (DW). Meanwhile, *Gracilaria tikvahiae* and *Eucheuma denticulatum* (Rhodophyta) have lower quantities with values between 2.8 and 4.5 μg $g^{-1}$ DW of total chlorophylls.

### 2.2. Carotenoids

Carotenoids are accessory pigments that assist chlorophylls in photosynthesis [20] and are divided into two main groups: carotenes and xanthophylls. Some carotenes are detected in seaweed species, but *α* and β carotenes are the most important [38]. α-Carotene is mainly found in Rhodophyta, while it is almost absent in Chlorophyta and Ochrophyta [37]. β-Carotene is found in all groups (Table 1) but is the most abundant in Chlorophyta and Ochrophyta, whereas it is found in smaller concentrations in Rhodophyta [39].

Xanthophylls have multiple biological activities [40] and are also detected in all seaweed groups. The most common are siphonaxanthin, neoxanthin, fucoxanthin, violaxanthin, diadinoxanthin, antheraxanthin, zeaxanthin, and lutein (Table 1). Fucoxanthin, the most frequently found xanthophyll in brown macrophytes, has been receiving more attention in scientific research for use in multiple sectors, such as cosmetic, food, nutraceutical, and pharmaceutical industries and as a feed additive in aquaculture and poultry farming [20,41]. The most frequently used species for the production of this pigment are *Saccharina japonica* (kombu), *Undaria pinnatifida* (wakame), and some diatoms [42]. However, among recent scientific studies, the best results for fucoxanthin concentration have been found in *Himanthalia elongata*, *Myagropsis myagroides*, and *Dictyota dichotoma* (18.6, 9.02, and 4.66 mg $g^{-1}$ DW, respectively) [43].

### 2.3. Phycobilins

Phycobilins, also called phycobiliproteins (PBPs), are accessory photosynthetic pigments [44], highly colored and water-soluble proteins [35,38]. PBPs have been widely used in the food, cosmetic, pharmaceutical, and biomedical sectors due to their characteristics, such as antioxidant capabilities and free-radical activities [39]. Another application of extracted phycobilins concerns nutraceutical potentials, which have been described as having anti-inflammatory, antiviral, antitumor, and liver-protecting properties [33,45].

Rhodophyta contain high PBPs concentrations, being responsible for the red to red-black color of red seaweed and masking the color pigments of chlorophylls and carotenes [8,46]. PBPs are classified into two large groups, phycoerythrin (PE) and phycocyanin (PC), based on their color.

PE is mainly and widely used as a red coloring agent in the food

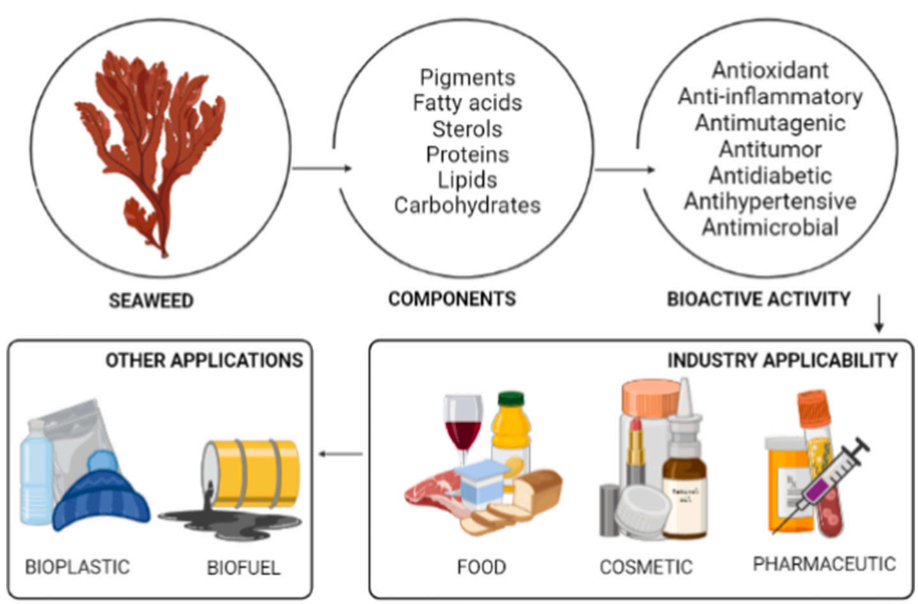


**Fig. 1.** Applicability of seaweed components and their bioactivity. Own elaboration, adapted from Echave et al. [13].

**Table 1**
Pigment composition of macroalgae review. C: Chlorophyta; R: Rhodophyta; O: Ochrophyta.

| | Pigment | | C | R | O | Application in the food industry | References |
|---|---|---|---|---|---|---|---|
| Chlorophylls | Chl *a* | | X | X | X | Natural colorant | ([26], [27]) |
| | Chl *b* | | X | | | Inactivation of microorganisms | |
| | Chl *c* | | | | X | | |
| | Chl *d* | | | X | | | |
| Carotenoids | Carotenes | α-carotene | | X | | | ([28], [29], [30], [31]) |
| | | β-carotene | X | X | X | | |
| | Xanthophylls | Antheraxanthin | X | | | Natural colorant | |
| | | Lutein | X | X | | Functional additive | |
| | | Neoxanthin | X | | | Stabilizing agent | |
| | | Siphonoxanthin | X | | | Emulsifying agent | |
| | | Violaxanthin | X | | X | Aroma precursors | |
| | | Zeaxanthin | X | X | | | |
| | | Fucoxanthin | | X | X | | |
| Phycobilins | Phycocyanin | | | X | | Natural colorant | ([32], [33], [34]) |
| | Phycoerythrin | | | X | | Fluorescent agent<br>Stabilizing agent | |

industry. Furthermore, its use in the pharmaceutical industry is continuously increasing due to its antioxidant and cytotoxicity against colon cancer cell lines, as it reduces the viability of these cells [47]. Previous studies have demonstrated that the anti-tumor effect resulting from its antioxidative activity improves apoptosis, gene expression, and immunity. Therefore, PE could be a potential drug for cancer prevention [48]. Red seaweed has a high PE content; however, they are almost non-existent in green and brown algae (Table 1). Kumar et al. [36] found a PE content from 1.4 to 3.9 mg $g^{-1}$ and 2.5 to 5.3 mg $g^{-1}$ fresh weight (FW) in Chlorophyta and Ochrophyta, respectively, while Rhodophyta contained 10.20 to 24.64 mg $g^{-1}$ FW.

Compared to PE, PC obtained from red macroalgae has been less studied. However, both PBPs share multiple applications. For instance, PC is the most commonly used natural blue pigment in the industry due to its dark color, which no other natural pigment has [38]. In addition to the nutritional values used as food and feed, PC also has pharmaceutical and bioactive potential as an anti-cancer, anti-inflammatory, anti-oxidative, anti-irradiative, and neuroprotective agent [34,49]. In addition, PC has additional advantages: the best stability under heat and light exposures, health-promoting benefits [38], and the key to new and numerous patents. Meticulous Market Research [50] pointed to PC development in the market globally due to the requirement for natural alternatives over synthetic products. That exhaustive report about PBPs also points out that specifically formulating PC to be nutraceutical agents will lead the global market in the next years. The global PC market is expected to grow to reach US$245 million by 2027.

## 3. Proteins

Seaweed are well-known sources of proteins. These proteins contain all the essential amino acids and are a rich source of bioactivity with potential functional properties [45,51]. Their multiple applications as food and pharmaceutical ingredients make them interesting compounds for use in different industries [52,53]. The main types of proteins and derivatives found in seaweed can be identified as peptides, enzymes, glycoproteins, lectins, amino acids [34,54], and PBPs, the latter being characteristic of red macrophytes [52]. The most abundant amino acids in seaweed are glycine, alanine, arginine, proline, glutamic, and aspartic acids [34,52]. In addition, the glycoproteins and lectins of seaweed are very interesting, attracting experts in the pharmaceutical industry [13,55].

Furthermore, the quality of animal proteins, such as those in milk or meat, is higher than seaweed proteins, although the quality of other vegetal sources of proteins such as wheat, rice or beans has slightly lower quality [56,57]. Consequently, the dietary intake of a mixture of proteins from seaweed could be a nice alternative for easily providing this high-quality component. Among seaweed, the highest protein concentrations are found in red algae, up to 49 % (Table 2), which is similar in quantity to other conventional foods rich in proteins, such as soybean, cereals, eggs, and fish [51]. The protein content of brown seaweed is relatively less than that of green seaweed (5–20 and 8–30 % DW, respectively; Table 2) [8,23]. There are variations in protein content in different species connected by geographical location and seasonal and environmental factors, such as water temperature, salinity, light irradiation, and wave force, which could affect the nutrient supply [46,51]. The maximum values in protein content have been described for winter and early spring [23].

## 4. Lipids

Lipids are essential for all living organisms as components of membranes, energy storage compounds, and cell signaling molecules [8]. Although humans and other mammals synthesize lipids, some essential lipids must be obtained from dietary food. Seaweed have a high variety of lipids, neutral (fatty acids, triglycerides, and sterols) and complex lipids (glycolipids (GL) and phospholipids (PLs)) [61], but at low levels compared to other sources. PUFAs (omega-3 polyunsaturated fatty acids) are mainly known and are recognized for their health benefits [60] and are mostly found in Ochrophyta. Among the health benefits of lipids, anti-inflammatory effects have been studied from crude extracts,

**Table 2**
Nutrient composition (proteins, lipids and carbohydrates) of selected species of macroalgae (% DW) from previously reported studies [16,46,51,55,58–60].

| Species | | Proteins | Lipids | Carbohydrates |
|---|---|---|---|---|
| Chlorophyta | *Caulerpa lentillifera* | 10–13 | 0.8–1.1 | 38–59 |
| | *Caulerpa racemosa* | 8–19 | 2 | 33–43 |
| | *Codium fragile* | 8–11 | 0.5–1.5 | 39–67 |
| | *Codium tomentosum* | 17 | 1.4 | 60 |
| | *Ulva lactuca* | 10–30 | 0.6–3 | 36–43 |
| | *Ulva rigida* | 15–19 | 0.9–2 | 43–60 |
| Rhodophyta | *Chondrus crispus* | 11–21 | 1–3 | 55–68 |
| | *Gracilaria chilensis* | 13 | 1.3 | 61 |
| | *Gracilaria gracilis* | 7–25 | 0.9 | 53 |
| | *Osmundea pinnatifida* | 20 | 1.8 | 57 |
| | *Palmaria palmata* | 8–35 | 0.73 | 46–56 |
| | *Porphyra* spp. | 24 | 2.1 | 52 |
| | *Pyropira* tenera (formerly *Porphyra tenera*) | 33–47 | 0.8 | 44 |
| | *Porphyra umbilicalis* | 29–39 | 0.3 | 43 |
| Ochrophyta | *Fucus vesiculosus* | 6–14 | 1.9 | 46 |
| | *Himanthalia elongata* | 5–15 | 0.5–1.1 | 44–61 |
| | *Laminaria digitata* | 8–15 | 1 | 48 |
| | *Saccorhiza polyschides* | 16 | 3.3 | 52 |
| | *Saccharina japonica* | 11 | 1.4 | 30 |
| | *Undaria pinnatifida* | 12–20 | 1.5–4.8 | 45–51 |

fractions, and isolated complex lipids, principally from Ochrophyta and Rhodophyta [62].

As previously stated, slightly higher values have been found in brown macroalgae, from 1 to 4.8 % DW, while green and red species show very low lipid contents, from 0.3 to 2.1 %. Similar lipid ranges have been obtained for the same species of macroalgae by different authors (Table 2). The amount reported by Milinovic et al. [16] for *U. pinnatifida*, which is highly consumed in Europe, was the highest found (4.8 %). There are several studies on the variation in lipid concentrations, which depend on geographical, seasonal, and environmental conditions, describing the highest values in winter and the lowest in summer and autumn typically [46].

## 5. Carbohydrates

Seaweed are a rich source of carbohydrates, which are equivalent to human glycogen, and are used as an energy source to carry out many life processes [8,63]. They can be used for diverse products, such as food, cosmetics, textile, paper, and building industries. In addition, they are used in human medicine and pharmacology for their antimicrobial, antiviral, antitumor, anticoagulant, and fibrinolytic properties [64], which stimulate the immune response [7].

The main carbohydrates in seaweed are in polysaccharide form, which includes relevant bioactive compounds, such as carrageenan, agar, alginate, cellulose, laminaran, ulvan, and fucan [65–67]. Although carbohydrate levels can also vary by species, season, and cultivation conditions [46], all seaweed groups show very similar carbohydrate contents, with values between 30 and 68 %. These levels tend to be slightly higher in Rhodophyta (Table 2), followed by Chlorophyta and Ochrophyta [58]. Green seaweed are rich in ulvan, brown algae in alginates, and red algae in carrageenans and agars [68], which are principally extracted from the genera *Chondrus*, *Eucheuma*, *Gigartina*, *Iridaea*, *Furcellaria*, and *Hypnea*. Among them, *Chondrus crispus* showed the highest values of carbohydrates, comprising almost 70 % of its biochemical compounds [69]. Ulvan is a sulfated polysaccharide [70] extracted principally from the genus *Ulva*, which can interact with relevant biological molecules given different viscosities and can be used to prevent food deterioration due to its antioxidant properties [71]. The main phycocolloids, agar, alginates, and carrageenans are those with the highest economic and commercial significance since these polysaccharides exhibit high molecular weights, high viscosity, and excellent gelling, stabilizing, and emulsifying properties. E-406, E-400, and E-407 (agar, alginates, and carrageenans, respectively) are some examples of European code additives used in food industries [59].

## 6. Metals and iodine

Concerning chemical contamination, seaweed consumption could be associated with the transfer of high-risk metals to humans due to their high capacity for bioaccumulation; thus, it is important to know the values of metals in seaweed [9]. Metal concentrations in macroalgae depend on multiple factors [51], such as the environmental conditions in which they grow and the quality of the surrounding water [19]. In general, green macrophytes have higher metal bioaccumulation than red and brown macrophytes [16].

In Europe, the only requirement established by Regulation (EC) N$^{o}$ 178/2002 determined that only safe foods will be marketed [72]; therefore, the European Union Recommendation (EU) 2018/464 suggested the control of the presence of arsenic, cadmium, iodine, lead, and mercury in seaweed, halophilic plants, and products based on seaweed [73]. Respecting contaminant values, the Commission Regulation (EC) 1881/2006, which established the maximum levels for certain contaminants in foodstuffs, only stipulated a level of cadmium in seaweed used as a food supplement [74]. This value is a maximum content of 3 mg kg$^{-1}$ FW, as shown in European Regulation N$^{o}$ 629/2008 [75]. Regarding the other contaminants, France was the first European country to make a specific assessment of chemical contaminants in the use of macroalgae for human consumption as food substances. The recommendations are for maximum levels of inorganic arsenic, cadmium, lead, and mercury in alimentary macroalgae [76].

In addition to metals, it is important to determine iodine [51], which could be in high concentrations in some algae. It is an essential element for the synthesis of thyroid hormones, but excessive consumption can contribute to an increase in thyroid pathologies. Several studies by the Spanish Agency for Food Safety and Nutrition (AESAN) have quantified these substances and determine how their processing (drying, freezing, etc.) influences iodine values in macroalgae. In France, a maximum level of 2000 mg kg$^{-1}$ DW of iodine is recommended for all species, with caution in people with thyroid pathologies (who also take medication related to iodine), heart or kidney diseases, and pregnant women, who should not consume it nor its derived products.

Therefore, due to the absence of European regulations that specifically regulate the content of metals and iodine in algae, the criteria established in the recommendations of the French Food Safety Agency (AFSSA) are normally used (Table 3).

**Table 3**
Maximum levels (mg kg$^{-1}$ [=μg g$^{-1}$] DW) of heavy metals and iodine authorized in algae (vegetables or condiments) [76].

| Residue | Values |
|---|---|
| Inorganic Arsenic (As) | 3 |
| Cadmium (Cd) | 0.5 |
| Mercury (Hg) | 0.1 |
| Lead (Pb) | 5 |
| Tin (Sn) | 5 |
| Iodine (I) | 2000 |

## 7. Applications

For centuries, seaweed has been widely used worldwide. In fact, there are many actual and potential uses with high economic importance, such as biofertilizers [77,78], bioplastics, feed products, pharmaceutical and cosmetic development products [79], and biological water indicators [80,81]. Furthermore, they are used to fight global challenges, such as climate change, as an alternative food resource to cope with population growth [82], as renewable energies, and as $CO_2$ sinks, providing a sustainable circular bio-economy strategy [83]. For example, Hadjkacem et al. [84] exposed the use of *Halopteris scoparia* in the production of alternative energies and in fighting environmental challenges. Furthermore, Binhweel et al. [85] and Shabarish et al. [86] used *Chaetomorpha antennina* and *Ulva lactuca* as potential sources of biohydrogen biofuel and biodiesel, respectively. Nevertheless, even though the uses of algae by humans are diverse and although it is probably the oldest use in medicine, nowadays the most widespread use is related to consumption in the gastronomic sector.

### 7.1. Direct consumption

Seaweed has been consumed for a long time, mainly in Asian areas, such as Japan, China, and Korea [87]. Some studies have shown that the Asian diet, which consumes high amounts of seaweed, is related to a healthy life [88], concerning all bioactive compounds with great benefits to human health [89]. The consumption of seaweed throughout history shows a high diversity of consumption ways: raw or fresh, directly cooked (boiled or salted), dried or dehydrated, fermented, or preserved in salt or with some other ingredient, such as oil [90].

Concerning algal species, wakame, nori, and kombu (*U. pinnatifida*, *Porphyra* spp., and *S. japonica*, respectively) are the most commonly consumed species, especially in Asian areas (Fig. 2) [78]. Wakame is one of the most commonly consumed species of macroalgae, and it is added to multiple foods as a principal ingredient. In addition, *U. pinnatifida* is

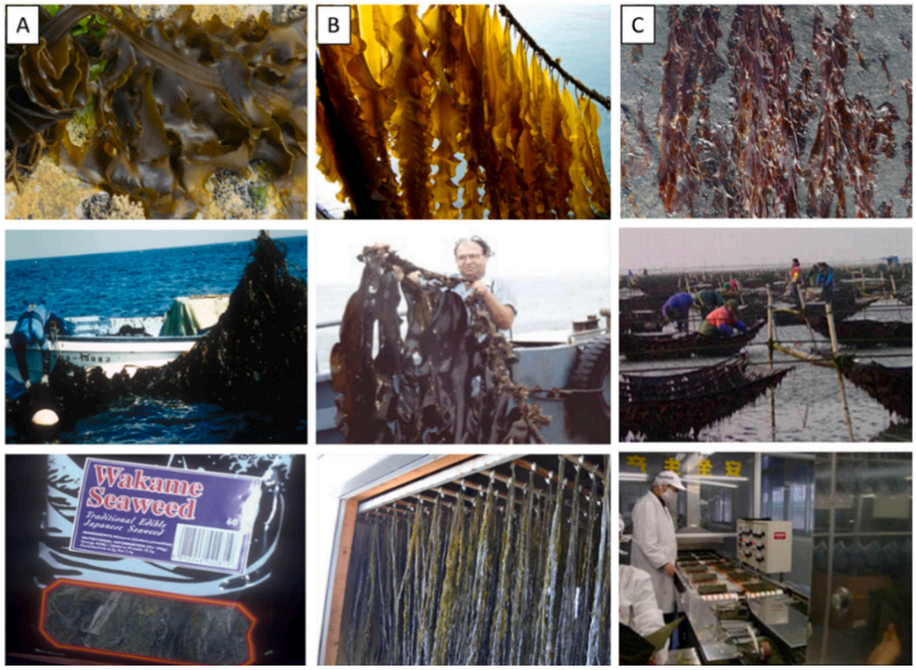


**Fig. 2.** Main consumed species, in their natural environment (first row), in natural collection (second row) and treated for consumption (third row). In columns (A) *Undaria pinnatifida* (wakame), (B) *Saccharina japonica* (kombu) and (C) *Porphyra* spp. (nori). Obtained from [91,92], and own photography from Hakodate, Japan.

an excellent source of nutrients [93]. Nori contains dietetic components of good quality that constitute around 40 % of its mass. It is famous globally but especially in Asia for sushi [94,95]. Kombu is the Japanese name for dried seaweed derived from the *Saccharina* genus, normally *S. japonica* (formerly *Laminaria japonica)*, and it is also used as a food supplement [96]. There are other important consumed species, such as brown algae, the Japanese-called hiziki (*Sargassum fusiforme,* formerly *Hizikia fusiformis*) [10] and the genera *Ascophyllum* or *Fucus* are highly consumed [97] and also used in actual food supplements [18]. Among the green ones, the genera *Ulva* and *Caulerpa* are some edible representatives [98] used mainly in salads and sushi due to their grape appearance [99]. Concerning red seaweed, one of the most popular macroalgae for human consumption is dulse (*Palmaria palmata*). Furthermore, *C. crispus* and *Gracilariopsis longissima* (ogonori) are also highly consumed [81,100].

### 7.2. Seaweed-derivatives industrial food products

New consumption habits and the commitment to creating and designing innovative foods and flavors have favored the introduction of seaweed and their derivates in the actual food industry [81,90], being considered the food of the future [101]. For example, in some daily products, such as milk, bread, vegetables, meat, or fish [102], the incorporation of seaweed has improved their nutritional characteristics, increasing the concentrations of calcium, potassium, sodium, magnesium, and iron [103]. In addition, there are new trends that focus on the use of seaweed to produce protein-based food, especially to substitute for other plant-based protein sources. As the demand for plant-based protein sources has been developing through population growth, the production of seaweed-based functional food on an industrial scale is predicted to grow exponentially in the next few decades [101]. Multiple products are seaweed-based, highly important economically and gastronomically, and are included in our daily diets indirectly, such as agar, alginates, carrageenans, or pigments [104].

#### 7.2.1. Agar

Agar is a common name for galactans. It is a formulation of agarose, agro-pectin, and other polysaccharides [105]. Around 80 % of the agar produced worldwide is applied in the food industry. Many of its food applications take advantage of the ability to display gels with unique properties. It can be found in different forms: powder, sticks, flakes, or strips, which gives it great versatility as an additive. It dissolves in hot water so that when it cools, it forms a gel. In addition, agar is also used as a stabilizer and thickener, since its gelling properties withstand high temperatures [81]. The quality of the agar mainly depends on the chemical properties related to environmental factors and the life cycle. Depending on the quality of the agar, it is used for different purposes [106]. Low-quality agar is specially used in food products, such as additives, but it is also used for paper, textile, and adhesive products in other industries. In contrast, high-quality agar is used in the pharmaceutical or biotechnological industries [106]. The most frequently used species for agar extraction belong to Rhodophyta and to the genera *Gracilaria* and *Gelidium*, mainly from *Gelidium corneum*, due to their high quality and specific uses [81,104].

#### 7.2.2. Alginates

Alginates are polymers formed from mannuronic and guluronic acid [106]. They are non-toxic hydrogels with excellent industrial properties. High-quality alginates confer great gelling and thickening power. In the food industry, they are usually found in powder form. Their thickening properties have various applications: increase the viscosity of sauces or creams, improve the texture of yogurt, reduce the sedimentation of the pulp in fruit drinks, and favor the mixing of components in emulsions. In addition to thickening, they are also used as stabilizers (e.g., ice creams), as gelling agents (e.g., stuffed olives), and as conservative agents (e.g., frozen food where oxidation is prevented). The power of this gel depends on the presence of calcium ions, and unlike other gels, the alginate does not melt when heated, which is a very useful property for some preparations [81].

Moreover, some studies have shown that alginates exhibit promising antitumor and antibacterial activities, opening the possibility for their use as active ingredients in new drugs [78]. Additionally, the cosmetic and textile industries are strong consumers of alginates in the preparation of dyes, toothpaste, and shampoos [97,107]. Alginate is found at concentrations up to 40 %, depending on the seaweed species, but the amount and composition of the alginate depend on the species, habitat, season, and area of the thallus. There are many species with high potential for alginate as a food or derivative product, but mainly alginate producers belong to Ochrophyta [7]. *Laminaria*, *Ascophyllum*, and *Lessonia* are the main genera for extraction [104].

*7.2.3. Carrageenans*

Carrageenans are sulfate polysaccharides that are not assimilable in the human digestive tract and are obtained mainly from red seaweed. Carrageenans are one of the main texturizing agents in the food industry after gelatin (animal) and starch (vegetable). There are several types of carrageenan, each of which has different properties, depending on the species and the extraction process: kappa, iota, and lambda [7]. Carrageenans have different applications in the food industry due to their high capacity to bind to proteins, which makes them ideal as stabilizers [108]. The use of stabilizers in dairy products and ice cream prevents the formation of ice, which is usually produced. Chocolate milkshakes also contain this component, which allows cocoa particles to be kept in suspension. They are also used in meat products, such as prepared hamburgers, keeping proteins and liquids together, and avoiding the use of other unnatural additives. Carrageenans have a high commercial value, and some applications are being developed related to them, mainly because they can form thermoreversible gels with applications in the cosmetic (e.g., hair conditioning agents and shampoo) [109], pharmaceutical (e.g., drugs, tissue engineering, antivirals, and capsules of pills), and chemical (textile, paper) industries [78,81]. The main producers of carrageenan belong to the genera *Chondrus*, *Kappaphycus*, and *Eucheuma*.

*7.2.4. Fucoxanthin*

Fucoxanthin is a xanthophyll carotenoid that is hydrolyzed to fucoxanthinol in the gastrointestinal tract and further converted in the liver. It has a unique chemical structure that confers benefits and effects on human health. Some institutions have identified fucoxanthin as the principal factor in the healthy diet of Japanese people [42]. This pigment and its metabolites have anti-inflammatory, anti-cancer, anti-obesity, anti-diabetic, and hepatoprotective effects [79,110] and are leading in supplements and enriched foods. Moreover, it is a secure pharmaceutical component that can successfully control the development of cancer by inducing apoptosis and the end of the cell cycle [42,111]. These potential applications are very promising and are expected to reach US$120 million next year. Algatechnologies Inc. created FucoVital™, the first fucoxanthin health food product derived from algae, and an innovative product for liver health. However, the commercialization of fucoxanthin is almost non-standardized because the extraction yield is very variable and depends on the species and extraction method. In most reviews, fucoxanthin production has been poorly discussed, and bioactivity is the main topic [41,42,61]. Nevertheless, easy access to seaweed converts this pigment into an economic and ecological alternative that provides a natural ingredient, avoiding chemical compounds [61]) Fucoxanthin is abundant in brown seaweed from the genera *Undaria*, *Laminaria*, *Sargassum*, and *Cystoseira* [40] and in many microalgae species [112].

## 8. Culture

Natural populations of algae are a useful and exploited resource, and due to the globalization process over time, the consumption and use of macroalgae in multiple sectors are increasing exponentially. The globalization process has stimulated the growth of new harvesting and cultivation techniques that supply the growing commercialization of algae worldwide [113]. Although seaweed aquaculture has been demonstrated to be the most sustainable method of seaweed production, manual harvesting has not been lost in many areas of the world [81]. Furthermore, in the process of stimulating yield, mechanized techniques are increasing, migrating to new land techniques. Among the multiple methods of these land-farming techniques, the yield of seaweed has shifted from small-scale ("*indoor*") to large-scale ("*outdoor*") production [14]. *Indoor* cultivation generally refers to the first stages of cultivation that are usually carried out in small closed spaces, such as tanks or pools, even in laboratories, where the reproduction stages are grown to stimulate the development and efficiency of production. However, *outdoor* cultivation refers to land crops in open-air spaces. These cultures usually occupy larger land spaces, so there are many companies or industries specializing in them. This kind of cultivation can even be developed in controlled areas of the open sea in mariculture [114]. Increasing the global production of seaweed requires an understanding of the key points that currently limit its production. Some studies have developed models to estimate the productivity of selected species in determined areas. Models based on ecological and environmental parameters are useful for the management and sustainable exploitation of selected species in determined areas [115].

Globally, 96 % of algae production comes from aquaculture [8]. The seaweed industry occurs in many countries around the world but is dominated by aquaculture in Asian areas (Table 4). Global aquaculture production in 2020 reached a record of 122 million tons, with 35.1 million tons being algae. This amount represents around US$16500 million [91], a considerable increase compared to the US$6700 million of global seaweed harvest in 2013 [7].

Among the most cultivated macrophytes (Table 5) are the genera *Porphyra* (nori), *Eucheuma*, *Kappaphycus*, and *Gracilaria* for red seaweed, *S. japonica* (kombu) and *U. pinnatifida* (wakame) for brown seaweed, and *Ulva*, *Caulerpa*, *Codium*, and *Enteromorpha* for green seaweed [19,81,117].

Wild seaweed presents a widely variable nutritional and biochemical composition, but under culture conditions, these values can be controlled, providing new ways to standardize, focus, and control interesting compounds of seaweed [17,118]. The success of the cultivation of macroalgae depends on good knowledge of the species to be cultivated, covering aspects of the biological cycle, reproduction, physiology, and ecology [5]. Therefore, it is important to review information concerning the biology of macrophytes to culture and the aspects related to them and the farming area, which facilitates the identification of optimal harvesting species, areas, and periods. Furthermore, it is essential to install specific regulations of "good practice manuals", which guarantee sustainability and equality in the sector, focusing on establishing key points and strategies that ensure their sustainable development over time. In fact, the definition of these regulations has already been developed and initiated in many global areas [119].

## 9. Weaknesses of algal applications

The seaweed sector has several weaknesses that need to be considered. Related to human health, it is necessary to consider some negative points in the use and treatment of algae as food and derivatives in gastronomy [120]. The 2018/464 European Commission [73] recommends limiting the use of some European macroalgae species as food [15]; therefore, the exhaustive characterization of macroalgae for consumption is essential. Regarding contaminants, seaweed accumulates metals and iodine from surrounding waters; consequently, it is vital to carefully evaluate the composition of algae, as well as their possible risks concerning food safety due to the presence of microorganisms and high

**Table 4**
Distribution (%) of seaweed aquaculture production by regions until 2020 [116].

| % | 2010 | 2020 |
|---|---|---|
| Africa | 0.69 | 0.30 |
| America | 0.06 | 0.07 |
| Asia | 99.18 | 99.54 |
| Europe | 0.01 | 0.06 |
| Oceania | 0.06 | 0.03 |

**Table 5**
Top cultivated seaweed and approximate production (thousand tons, FW) [91,18].

| Seaweed species | 2005 | 2010 | 2015 | 2020 |
|---|---|---|---|---|
| *Saccharina japonica* | 5800 | 6525 | 10313 | 12470 |
| *Eucheuma* spp. | 987 | 3481 | 10190 | 8130 |
| *Gracilaria* spp. | 933 | 1691 | 3881 | 5180 |
| *Undaria pinnatifida* | 2440 | 1537 | 2297 | 2810 |
| *Porphyra* spp. | 703 | 1072 | 1159 | 2220 |
| *Kappaphycus alvarezii* | 1285 | 1888 | 1754 | 1604 |
| *Sargassum fusiforme* | 115 | 97 | 209 | 292 |

concentrations of metals (and other contaminants) and iodine [120]. It should not be generalized for whole seaweed groups, and the references for different species must be classified for each component and for each site [121].

Several studies have provided valuable evidence of the benefits of seaweed aquaculture development due to its simplicity, eco-friendly characteristics, low initial investment (compared to animal aquaculture), and cleaning of coastal areas to enhance biodiversity and fisheries. However, there are some negative points related to the treatment and culture of seaweed, and it is necessary to consider some key points related to the biological, scientific, and economic aspects of seaweed cultivation [69,122].

Concerning biological aspects, it is necessary to evaluate the different points regarding the aquaculture of seaweed to preserve the quality of the culture and to care for the impact produced on the sea [69]. Invasive species are widely recognized as the main risk to marine biodiversity, altering the relative abundance of native species and affecting the structure of the ecosystem and, consequently, the local economy [123,124]. For this, it is vitally important to cultivate local species, in areas that are not widely invaded by another invasive species [120]. Problems derived from the introduction of invasive seaweed species are related to a lack of adequate regulations for their introduction [125]. Furthermore, actual globalization brings some challenges, climate change supposes an increase in temperature, water acidification, as well as a rise in sea level, entailing a challenge to the biological cycle of many seaweed species [122]. Moreover, human development in urban areas causes the deterioration of marine ecosystems. To fight these problems, the challenges faced by scientists regarding seaweed aquaculture are the development of disease and herbivore resistance, the fast growth of seaweed species, and the improvement of the aquaculture systems to be more robust, cost efficient, resist storm events, and maintain cultures for more time [69,126]. Land aquaculture was practical thousands of years ago, but the sea is still uncultivated [127] due to its dependence on multiple factors that have been less studied, such as the species farmed, the purpose of farming, market prices, and the scale of cultures. Finally, economic thoughts must be considered. Seaweed cultivation throughout the world is still difficult with a possible and sustainable methodology, which should be economically viable and productive [126].

## 10. Future perspectives

The use and consumption of seaweed and seaweed-based food ingredients around the world have grown in recent decades and are expected to continue to increase. Seaweed production is a poorly established industry; therefore, specifically for the European seaweed food-based industry, there are some challenges [113]. It is necessary to determine some values related to the health risk regarding metals and iodine, as well as to define the microbiological rate of organisms allowed in human food. In addition, standardizing and defining the chemical compounds present in each species are necessary. Considering these needs, an important challenge is establishing guides and regulations to ensure these tasks (Fig. 3). They must include regulation of algae quality and a manual of best practices for the culture that prevents environmentally and health-harmful seaweed aquaculture [17]. For this, it is important to know the bioavailability of seaweed, as well as its life cycle. The investigation of seaweed is essential to use it as an alternative, promoting its sustainable use, an ecological source for food, and other applications, such as feed, cosmetics, fertilizers, and fuel [128]. Algal transgenic biotechnology shows high potential for more efficient and specialized production of food compounds, such as carotenoids, PUFAs, pigments, and proteins with super producer seaweed [105]. It is also necessary to identify new algae species with valuable properties desired by these industries (e.g., biochemical and nutraceuticals), obtain their approval as novel foods, and finalize commercial production. Multiple studies have identified promising algae as novel foods, but the current legislation procedures are incomplete. They require revision for a quicker, cheaper, and safe approval process for novel seaweed species [129].

## 11. Conclusions

Many people around the world use algae as food. Currently, the use of algae as a potential food and feed ingredient in functional foods is growing due to consumer interest in food and health. Seaweed contains highly nutritional and bioactive compounds (such as proteins, minerals, and vitamins) and shows therapeutic applications for health and disease management (including anticancer, anti-obesity, and antiviral

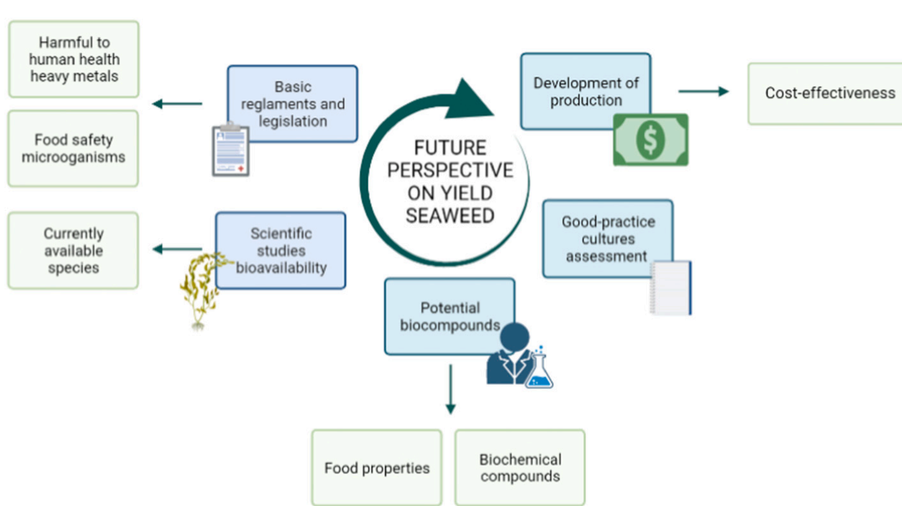


**Fig. 3.** Summary of the key points in seaweed development. Own elaboration.

properties). In relation to the increase in the demand for seaweed and their derivatives for nutrition and consumption, the interest in local species is starting to increase; thus, the correct focus on seaweed and derivative products is crucial for the development of a sustainable gastronomic sector. In addition, their use is important to be implemented and launched in a Blue Economical context to promote economic growth and preserve the health of the oceans, being eco-friendly and sustainable. Progress in new cultivation technologies that can be more efficient and less harmful to the environment is crucial; therefore, there is a need to have multi- and interdisciplinary research groups working together to gain knowledge and optimize traditional aquaculture, reducing the culturing risks and enhancing new and more cost-effective facilities to improve seaweed quality.

## Abbreviations

| | |
|---|---|
| AESAN | Spanish Agency for Food Safety and Nutrition |
| AFSSA | French Food Safety Agency |
| Chl | Chlorophyll |
| FAO | Food and Agriculture Organization |
| GL | Glycolipids |
| PBPs | Phycobiliproteins |
| PC | Phycocyanin |
| PE | Phycoerythrin |
| PLs | Phospholipids |
| PUFAs | Polyunsaturated fatty acids |

## Statement of informed consent, human/animal rights

No conflicts, informed consent, human or animal rights are applicable.

## CRediT authorship contribution statement

**Marina Salido**: Conception and design, Methodology, Analysis and interpretation of the data, Resources, Drafting of the article and review & editing. **Manu Soto and Sergio Seoane**: Conceptualization, Project administration, Funding acquisition, Resources, Supervision, and critical revision of the article.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Marina Salido reports financial support was provided by University of the Basque Country - Bizkaia Campus. Manu Soto reports financial support was provided by University of the Basque Country - Bizkaia Campus. Sergio Seoane reports financial support was provided by University of the Basque Country - Bizkaia Campus.

## Data availability

No data was used for the research described in the article.

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