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Foods with microalgae and seaweeds fostering consumers health: a review on scientific and market innovations

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Abstract

Nutrition plays a crucial role in health promotion and disease prevention, and dietary-related factors are, in many cases, the leading risks for worldwide mortality and morbidity. Nowadays, consumer awareness of this fact has led to an increasing interest in food products that couple both these dimensions to an imperative third overall factor of interest—sustainability. Microalgae and seaweeds have in their composition a wide range of important multifunctional bioactive compounds which may possess cardiovascular protective, anti-inflammatory, anti-hypertensive, antioxidant, anti-coagulant, anti-proliferative, and/or anti-diabetic activities. In addition, they can constitute excellent ingredients for the food industry to be used in the development of value-added food products. This review provides an overview on the current scientific and industrial developments regarding food products incorporating microalgae and seaweeds. Furthermore, technological, nutritional, sustainability, and health benefits resulting from their incorporation in different food matrixes are also explored.

Keywords Algae · Seaweeds · Bioactive compounds · Functional foods · Health benefits

Introduction

Nutrition plays a crucial role in health promotion and disease prevention, and dietary-related factors are, in many cases, key risk factors contributing to worldwide mortality and morbidity (Esposito et al. 2017). The perception of nutrition's impact on human health has changed the paradigm of food intake over the last few decades; focus has moved from single components of foods to dietary patterns that consider the synergistic effects of overall food consumption (Esposito et al. 2017). The Mediterranean diet is the most studied and scientifically documented dietary pattern with proven health benefits on reduction of overall mortality, specific mortality due to cancer and coronary heart disease, obesity, diabetes, mental health, respiratory diseases, as well as promotion of quality of life and healthy aging, among others (Dinu et al. 2018; Costa et al. 2019; Deligiannidou et al. 2019; Serra-Majem et al. 2019). The Mediterranean diet pattern is based on the use of olive oil as the principal source of fat; the high consumption of legumes, whole cereal grains as well as fruits and vegetables; the low consumption of red or processed meat; the low to moderate intake of dairy products, poultry, and fish; some wine consumption with meals; and the use of herbs and spices as salt substitutes (Esposito et al. 2017). In addition, healthy habits such as exercise practice and cooking techniques are also an important part of the Mediterranean lifestyle (Dernini et al. 2017; Serra-Majem et al. 2019). The Mediterranean diet is also an excellent tool to address one of the major challenges of our current society—sustainability (Dernini et al. 2017). According to the Food and Agriculture Organization (FAO), by 2050, food production will have to increase at least by 60% in order to feed the needs of an urbanized and growing population (Alexandratos and Bruinsma 2012). To meet this demand,

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it is imperative to perform radical changes in food production and consumption over the next decades taking into consideration the upcoming major environmental problems such as climate change and the increasingly degraded and stressed natural resources (Tilman and Clark 2014; Dernini et al. 2017). The Mediterranean diet may effectively address these problems and, in fact, it is an outstanding example of a sustainable diet model since it involves major nutritional and health benefits, has high sociocultural food value (it is currently considered an Intangible Cultural Heritage of Humanity by the United Nations), drives positive regional economic returns, and promotes biodiversity richness and lower environmental impacts (Reguant-Aleix et al. 2009; Dernini et al. 2017). Despite the extensive knowledge on the benefits of the Mediterranean diet, adhesion to this dietary pattern, even in Mediterranean countries, has been decreasing, especially among younger generations, probably due to several economic and social factors such as urbanization, loss of culinary knowledge and practices, and compulsory use of canteen and restaurants (Vilarnau et al. 2018; Serra-Majem et al. 2019). This loss of cultural heritage may lead not only to health problems such as overweight and obesity, undernutrition, and several diet-related chronic diseases, such as type 2 diabetes, several types of cancer, and neurodegenerative diseases, but also to changes in social, cultural, environmental, and economic factors (Belahsen 2014; Deligiannidou et al. 2019). Considering all these problems and in line with increasing consumer demands, it is imperative that the food industry invests in the development of foods that are in line with the Mediterranean diet criteria and that target health promotion, disease prevention, and environmental sustainability but are also convenient and ready to eat (Granado-Lorencio and Hernández-Alvarez 2016; Dernini et al. 2017). Organisms such as micro- and macroalgae (or seaweeds) are excellent ingredients to be incorporated in novel functional and in "grab to go" foods since they are a valuable source of functional components such as polysaccharides, vitamins, minerals, pigments, enzymes, proteins and peptides, lipids and polyunsaturated fatty acids (PUFA), phenolics, and other secondary metabolites scientifically described to possess cardiovascular protective, anti-inflammatory, anti-hypertensive, antioxidant, anti-coagulant, anti-proliferative, and anti-diabetic activities (Freitas et al. 2012, 2015; Teas et al. 2013; Boziaris 2014; Suleria et al. 2016; Wang et al. 2017; Wells et al. 2017; Nova et al. 2020). In this review, the current scientific and market innovations regarding foods incorporating microalgae and seaweeds will be covered. Furthermore, technological, nutritional, and health benefits from incorporation of these new ingredients in different food matrixes will also be explored.

Characteristics and novelties regarding seaweeds and microalgae

Seaweeds are photosynthetic plant-like eukaryotic organisms classified into three major groups, i.e., red algae (Rhodophyta), brown algae (Phaeophyceae), and green algae (Chlorophyta) (Wang et al. 2017). Their chemical composition is influenced by environmental factors such as salinity, temperature, pH, sunlight, physiological status, and carbon dioxide (CO_2) supply. Some of these organisms also can grow in very harsh environmental conditions (Wang et al. 2017). In consequence of environmental adaptations and taxonomic diversity, the macroalgae produce a wide range of novel bioactive compounds and metabolites such as PUFAs, polysaccharides, and phlorotannins. Additionally, they are a source of high biological value protein (Wang et al. 2017).

Microalgae are simple-structured microscopic photosynthetic microorganisms classified in several phyla that can synthetize complex molecules and produce biomass from CO_2, light energy, and nutrient elements (Shin and Lee 2013; Borowitzka 2018). Because of these simple growth requirements, microalgae can be used to sustainably produce high nutritional value molecules such as carbohydrates, lipids and proteins, and secondary metabolites with bioactive potential for humans such as PUFAs (namely, γ-linolenic (GLA), arachidonic (AA), docosahexaenoic (DHA), and eicosapentaenoic (EPA) acids), vitamins (A, B1, B2, B3, B6, B12, C, E, folic acid, and pantothenic acid), carotenoids (β-carotene, astaxanthin, lutein, zeaxanthin, fucoxanthin), chlorophylls, and phycobiliproteins (phycoerythrin, phycocyanin) (Buono et al. 2014; Sidari and Tofalo 2019; Zarekarizi et al. 2019).

In Eastern countries, seaweed consumption is deeply embedded in their daily dietary intake, and epidemiological studies have suggested that the ingestion of large amounts of seaweeds could be correlated with a reduced incidence of many of the chronic diseases that burden Western countries (Deleris et al. 2016). In Japan, according to data from the "National Nutrition Survey," in 2007, the daily intake of seaweeds was about 14.3 g per adult, contributing strongly to increase the intake of dietary fiber in the Japanese population (Fukuda et al. 2007; Deleris et al. 2016). The most consumed seaweeds in Japan are nori (*Pyropia* (*Porphyra*) *tenera*), Mozuku (*Nemacystus decipiens*), Hijiki (*Sargassum fusiforme* (previously named *Hizikia fusiformis*), Konbu (*Saccharina* (*Laminaria*) *japonica*), and Wakame (*Undaria pinnatifida*) (Fukuda et al. 2007; Deleris et al. 2016). The benefits of following a Japanese diet towards reduction of cardiovascular disease and cancer risks were analyzed in a cohort of 58,767 Japanese participants (23,162 men and 34,232 women) aged between 40 and 79 years old; an association was established between decreased risk of cardiovascular disease and all-cause mortality, especially in woman (Okada et al. 2018). In addition, Murai et al. (2019), in a cohort of 86,113 Japanese participants (40,707 men and 45,406 women) between 40 and 69 years old, concluded that seaweed intake is inversely associated with the risk of ischemic heart disease.

In more recent years, the novel characteristics have of seaweeds and microalgae also been explored in Western countries by the food, pharmaceutical, and nutraceutical industries given their remarkable potential for medical, industrial, and biotechnological applications (Boziaris 2014; Brown et al. 2014). Health benefits from algal bioactive compounds have been extensively studied by the scientific community registering promising health perspectives and therapeutic strategies for several chronic and degenerative diseases. Studies have been reporting evidence of health benefits from algal bioactive compounds such as polysaccharides, fibers, carotenoids, or other smaller molecules like peptides or polyphenols on atherosclerosis, several types of cancer, cardiovascular diseases and related risk factors, obesity, inflammation, neurodegenerative diseases, type 2 diabetes, gut health, bone health, and even antiviral and antioxidant activities (e.g., Pangestuti and Kim 2011; Atashrazm et al. 2015; Ricciardi et al. 2015; Lowenthal and Fitton 2015; Shimada et al. 2016; Wan-Loy and Siew-Moi 2016; Gabbia et al. 2017; Giffin et al. 2017; Nisha and Devi 2017; Olasehinde et al. 2017; Wang et al. 2017; Wei et al. 2017; Andrade et al. 2018; Caporgno and Mathys 2018; Gutiérrez-Rodríguez et al. 2018; Lee et al. 2019; Yan et al. 2019; Balasubramaniam et al. 2020; Nova et al. 2020). The burden of chronic and debilitating diseases in today's society claims for new effective treatments and preventive strategies. In this context, marine resources could be useful in the development of novel functional food products that might benefit the onset and prognostic of several diseases (Nova et al. 2020). In addition to their nutritional value and potential health benefits for human consumption, seaweeds and microalgae are also important from the environmental and sustainability points of view; many seaweed species are found in almost every ecosystem in the world, they grow fast, and certain species can even develop in saline conditions, without the need for fresh water, an overwhelming advantage when comparing with traditional agriculture (Buech 2018). Furthermore, algae for food applications may be processed using environmentally friendly processing methods such as autohydrolysis, taking full advantage of its bioactive compounds and promoting sustainability and a circular economy framework (Fradinho et al. 2020).

Nevertheless, several aspects need to be considered when developing food products with seaweeds and microalgae. These include consumer awareness and demand, bioavailability of bioactive compounds, cost-effectiveness, stability, and shelf life. In the case of microalgae, the fact that only a few species are authorized for human consumption because of strict food safety regulations also needs to be taken into consideration (Champenois et al. 2015; Sidari and Tofalo 2019). *Arthrospira platensis* (formerly *Spirulina*), *Schizochytrium* sp., *Scenedesmus* spp., *Chlorella* spp., *Haematococcus pluvialis*, *Dunaliella salina*, *Porphyridium purpureum*, *Aphanizomenon flosaquae* var. *flosaquae*, and more recently *Tetraselmis chuii* are among the microalgae species used for human nutrition (AECOSAN 2013; Champenois et al. 2015; Kavitha et al. 2016; Sidari and Tofalo 2019).

Given their richness in compounds with biological activity, seaweeds and microalgae can be used as functional ingredients in the food industry thus providing interesting products that will certainly satisfy consumer actual demand for foods that conjugate nutritional and health benefits with sustainability, are of easy culinary preparation, and present high convenience-"grab to go" concept. In the next section, scientific and market innovations regarding foods incorporating seaweeds and microalgae will be presented and discussed.

Food products incorporating seaweeds and microalgae

As described, seaweeds and microalgae are an excellent source of value-added compounds that may be incorporated in the development of innovative food products (Wells et al. 2017; Bhalamurugan et al. 2018). In fact, current consumers are much more selective in their food choices and the demand for cost-quality products that provide something "more" beyond standard expectations are in high demand (Goncalves and Kaiser 2011). Furthermore, these types of products drive a new paradigm for the food industry since they need constant scientific and technological adaptations and further investments in product development and target marketing (Goncalves and Kaiser 2011; Bhalamurugan et al. 2018). In Table 1, a list of some of the most recently developed food products incorporating seaweeds and/or microalgae is presented.

Snacks

Snacks with improved nutritional and health benefits have been in high demand over the recent years, especially among the younger generations, given their convenience and high practicality (Goncalves and Kaiser 2011; Potter et al. 2013; Wells et al. 2017). Lucas et al. (2018) aimed to develop snacks enriched with *A. platensis* (a cyanobacterium widely used as a food ingredient, Table 1) in order to improve associated nutritional value (Lucas et al. 2018; National Center for Biotechnology Information 2019). By incorporating 2.6% (w/w) of *A. platensis*, the authors achieved an increase of 22.6% (w/w) in protein content, 28.1% (w/w) in lipid content, and 46.4% (w/w) in mineral content without affecting the product's physical parameters' hardness and expansion index but with a significant impact on its color due to the strong

Table 1 Newly developed food products incorporating seaweeds and microalgae

Product	Microalgae incorporation	Biomass addition (dry power)	Health or/and technological benefits	References
Extruded snacks	*Arthrospira platensis*	2.6% (w/w)	- Increase of nutritional content in protein, lipids and minerals; - Physical parameters of the product (expansion index, hardness, water absorption index, and water solubility) not affected; - Significant impact on the color of the product with a negative impact on sensory analysis; - Enriched snacks presented thin cell walls (18.5 μm).	Lucas et al. (2018)
Corn snack	*Sirophysalis trinodis* *Polycladia myrica*	2 and 4% (w/w)	- Seaweed incorporation with no significant effect on flavor, odor and acceptance of the product; - Nutritional enhancement in protein, minerals and fatty acids; - Improved antioxidant capacity.	Etemadian et al. (2018)
Brown rice snack cereal bar	*Hoodia gordonii* (plant powder) and *Kappaphycus alvarezii* (seaweed powder)	From nine initial formulations, two were chosen based on sensory evaluation and characterized by proximate analysis: (i) 1.6% (w/w) plant + 2.8% (w/w) seaweed: (ii) 2.4% (w/w) plant + 2.8% (w/w) seaweed	- Plant and seaweed powders altered color - (samples became darker), texture (especially regarding to hardness) and proximate analysis (significant differences in fat, fiber, ash and carbohydrates) of all cereal bars. However, all the formulations presented, in general, good sensory acceptability; - Formulations with less quantity of seaweed and plant registered better acceptability regarding to color; - Both chosen formulations are a great potential source of dietary fiber.	Hajal et al. (2015)
Seaweed-based biscuit	*Ulva lactuca*	30, 40, 50 and 60% of seaweed with respective percentage of wheat flour (60, 50, 40, 30%), sugar (5%), and butter (5%)	- The best sensory-accepted biscuit was the one prepared with 30% of microalgae incorporation; - This product with low moisture and near neutral pH registered a shelf life of 8 weeks without developing pathogens or rancidity, low moisture ,and near neutral pH; - 10 malnourished children between 5 and 6 years old were supplemented with 30% seaweed-based biscuit for 2 months with a significant positive impact in weight, body mass index, body max percentile, mid-upper arm circumference, and total protein.	Jenifer and Kanjana (2019)
Cookies	*Arthrospira platensis* *Chlorella vulgaris* *Tetraselmis suecica* *Phaeodactylum tricornutum*	2 or 6% (w/w)	- Significant increase in antioxidant activity and phenolic compounds; - Stable and innovative green colors that varied between a blueish-green (*A. platensins*) to a brownish-green (*P .tricornutum*); - *A. platensis* provided a structuring effect on cookie texture.	Batista et al. (2017)
	Arthrospira platensis	2 or 5% (w/w)	- Nutritional enrichment in fiber, protein, and ash content; - Increase in phenolic compounds and antioxidant capacity.	Bolanho et al. (2014)
	Haematococcus pluvialis (Astaxanthin-rich microalgae)	5, 10, and 15% astaxanthin powder	- Significant reduction in the rate of glucose released during in vitro digestion; - Increase in the total phenolic content and antioxidant capacity; - Potential to lower the glycemic response of whole meal flour cookie. - Lower free glucose release was observed from cookies with 15% astaxanthin, followed by 10%, and then 5% astaxanthin in comparison with control cookies.	Hossain et al. (2017)
Cookies and pasta	*Nannochloropsis oculata*	1% (w/w)	- Stable color for 2 months of storage and increased firmness compared with control cookies and pasta; - Nutritional increase of omega-3 levels (eicosapentaenoic and docosahexaenoic acids);	Babuskin et al. (2014)
Pasta	*Dunaliella salina*	1–3% (w/w)	- Improved cooking quality (more weight and volume) and sensory characteristics (mouth feel and overall acceptability and flavor was not affected with up to 1% of microalgae);	El-Baz et al. (2017)

Table 1 (continued)

Product	Microalgae incorporation	Biomass addition (dry power)	Health or/and technological benefits	References
Yogurt	*Pavlova lutheri*	0.25 and 0.5% (w/v)	- Nutritional enhancement in calcium, iron, magnesium and potassium, phytochemicals and unsaturated fatty acids. - Increased concentrations of total n-3 PUFA; - Techno-functional properties of yogurt unaffected; - Sensory attributes specially regarding to color and flavor needs improvement; - Possible potent anti-inflammatory activity since this microalga has demonstrated this capacity in vitro.	Robertson et al. (2016)
	Omega-3-rich algal oil from *Schizochytrium* sp.	1264.69 ± 44.91 mg DHA	- Nanoemulsion technology improved bioavailability of omega-3 compared with bulk oil in vivo.	Lane et al. (2014)
Cheese	*Chlorella vulgaris*	2, 4, and 6% (w/w)	- Nutritional enhancement of functional compounds: high levels of potassium, magnesium, selenium, zinc, and iron; - Improved antioxidant potential.	Tohamy et al. (2018)
Powered food	*Arthrospira platensis*	750 mg per 100 g of product	- Estimated 19 months of shelf life; - Potential source of energy, protein, carbohydrates, dietary bioactive compounds, essential fatty acids, and vitamins.	Santos et al. (2016)
Breadsticks	*Chlorella vulgaris* *Arthrospira platensis*	1.5% (w/w)	- Increase in mineral content (iron and selenium); - Changes in texture and rheology (decrease in all textural parameters); - Impact on dough color with visual perception of green color; - Color and texture stability over 15 days of storage.	Uribe-Wandurraga et al. (2019)
Wheat bread	*Isochrysis galbana* *Tetraselmis suecica* *Scenedesmus almeriensis* *Nannochloropsis gaditana*	7.5 g per 500 g of sourdough starter (1.5% w/w)	- Changes in color, crust, and crumb (decrease of redness and increase of yellowness); - Increased viscosity even at low concentrations of microalgae; - Hardness, chewiness, and resilience not modified by microalgae addition.	García-Segovia et al. (2017)
Wheat flour dough and bread	*Chlorella vulgaris*	1.0, 2.0, 3.0, 4.0, and 5.0 g per 100 g of wheat flour	- Positive impact on dough viscoelastic and rheology characteristics with up to 3.0 g of microalgae addition; - Negative effect on flavor, texture, and dough rheology and increased bread aging with higher microalgae content; - No effect on kinetics of yeast fermentation or time required for fermentation.	Graça et al. (2018)
Bread	*Arthrospira platensis*	1 and 3% per 100 g of bread	- Significant increase in protein, minerals, and fat content; - Color of the product unappreciated by consumers especially in the product with 3% of algae incorporation.	Hafsa et al. (2014)
	Palmaria palmata	Bread (230 g) containing 5 g *P. palmata*	- Randomized placebo-controlled intervention trial with 2 groups: 20 participants consumed placebo bread and 19 participants bread with algae incorporation for 4 weeks; - Stimulated inflammation, increased serum triglycerides, and altered thyroid function in bread with *P. palmata* consumption group.	Allsopp et al. (2016)
Broccoli soup	*Arthrospira platensis* *Chlorella* sp. *Tetraselmis* sp.	0.5 to 2.0% (w/v)	- Increased content of polyphenols and higher antioxidant capacity; - Higher amount of bioaccessible polyphenols; - High acceptability indexes were obtained for soups containing microalgae at 0.5%.	Lafarga et al. (2019)
Dehydrated soup	*Arthrospira platensis*	15% (w/w)	- Excellent for nutritional enrichment: high protein, fiber, ash, and lipids content; - High chlorophyll content and improved antioxidant capacity; - Modifications in color (dark-green color), viscosity, water absorption, and solubility.	Los et al. (2018)

Table 1 (continued)

Product	Microalgae incorporation	Biomass addition (dry power)	Health or/and technological benefits	References
Soup powder	*Ulva lactuca* *Gracilaria verrucosa* (agar extract) *Kappaphycus alvarezii* (carrageenan extract)	2 different soups (w/w) 1): 2.5% *U. lactuca* and different % of agar (1 to 4%) 2): 2.5% *U. lactuca* and different percentages of carrageenans (1 to 4%,)	- Agar and carrageenan extracts revealed to be excellent nutritive thickener and gelling agents; - Improved apparent viscosity of the product; - Nutritional enhancement in minerals, specially calcium, potassium, magnesium, sodium and iodine; - Shelf life up to 3 months in ambient temperature; more than 6 months in deep freezer and 6 months in freezer storage.	Jayasinghe and Pahalawattaarachchi 2016
	Kappaphycus alvarezii (carrageenan extract)	5% (w/w)	- Nutritional enhancement specially in mineral content; - Consistency and flavor characteristics of soup not affected.	Jeyakumari et al. (2016)
Fish jerky	*Sargassum wightii*	0, 3, and 5% (w/w)	- Increase in total dietary fiber, macrominerals, and trace elements; - Addition of up to 3% did not affect the organoleptic quality and improved the antioxidant and microbial quality of the product.	Hanjabam et al. (2017)
Virgin olive oil	*Scenedesmus almeriensis* (carotenoids rich extracts)	0.1 and 0.21 mg mL^{-1}	- Changes in color, turning the product orange reddish; - Considerably nutritional enhancement in beta-carotene and lutein; - Oxidative stability improved giving a better shelf life quality to the product; - Fatty acids and tocopherol profiles not affected by microalgae extract; - Reduced peroxidation enhancing olive oil quality.	Limón et al. (2015)

green pigmentation of this microalga. Despite the less positive impact on its color, other attributes such as flavor, texture, taste, and overall acceptance were not affected by the addition of *A. platensis* resulting in an acceptability index of 82% by the panelists (Lucas et al. 2018). Similarly, Etemadian et al. (2018) developed successfully corn snacks nutritionally enhanced in protein, fatty acids and minerals, and with antioxidant potential by incorporating the seaweeds *Sirophysalis trinodis* (2% (w/w)) and *Polycladia myrica* (4% (w/w)) in the product (Table 1, Etemadian et al. 2018). *Hoodia gordonii*, a plant that grows in South Africa and Namibia, with proven effects in appetite suppression, was combined with the red seaweed *Kappaphycus alvarezii* to develop a functional brown rice snack cereal bar (Table 1). Although the combined incorporation of a plant and a seaweed affected both the color and the texture of the rice snack bar, it received good sensorial acceptability (Hajal et al. 2015). These ready-to-eat functional snacks are undoubtedly an interesting tool to fulfill society's demand for nutritional, healthy, convenient, and sustainable tasty foods; moreover as demonstrated by Jenifer and Kanjana (2019), these types of food products may also impact human life in more important dimensions. The authors developed a biscuit enriched with 30% (w/w) of seaweed *Ulva lactuca*, a low cost indigenous marine food highly prevalent in the Gulf of Kutch Coast of Gujara, and supplemented 10 malnourished children between 5 and 6 years old with the product for a period of 2 months (one serving (4 biscuits) constituting 60 g of formulated seaweed biscuit per day). Significant positive impacts were observed on body mass index, weight, body mass percentile, mid-upper arm circumference, and total protein of the tested subjects (Table 1). Functional enriched snacks with prolonged shelf life recurring to highly prevalent and nutritionally rich natural marine resources could really make a difference in the promotion of healthy and sustainable environments (Jenifer and Kanjana 2019).

Cookies are equally desired and highly consumed convenient snacks. However, this type of food product has, in general, a low nutritional value and a high sugar content (Bolanho et al. 2014). More recently, studies have been changing this trend by incorporating in cookies novel marine resources that could confer interesting nutritional and functional properties (Bolanho et al. 2014; Batista et al. 2017). For example, *A. platensis* was incorporated in cookies to improve their nutritional profile and antioxidant potential (Table 1). With the incorporation of 2 or 5% (w/w) of microalga, the authors achieved an interesting functional product nutritionally enriched in fiber, protein, and ash contents as well as in phenolic compounds and associated antioxidant capacity. However, formulations with 5% (w/w) of *A. platensis* biomass registered low scores for appearance, aroma, flavor, texture, and overall acceptability in the sensorial evaluation. In turn, the 2% (w/w) *A. platensis* cookie formulation registered no statistically significant differences in sensorial analysis compared with the control (cookie without microalgae incorporation) (Bolanho et al. 2014). This study raised an important topic regarding the development of food products incorporating microalgae. Nutritional enrichment and antioxidant improvement achieved with higher percentage incorporation (5% (w/w) microalgae) is hampered by reduced consumer acceptability at higher concentrations. The greatest challenge both for food development and industry application resides in finding the right balance between the amounts of microalgae percentage incorporation to achieve improved health benefits without jeopardizing sensory quality. A food product may present several health benefits, but if it is not tasty and attractive, very few consumers will be willing to buy it. Batista et al. (2017) also tested the effect of quantity of microalgae incorporated in cookies but tested a larger number of species. These authors evaluated the sensory, physical, and chemical properties; antioxidant activity; and in vitro digestibility of cookies enriched with one of two percentages (2% (w/w) and 6% (w/w)) of each microalga, i.e., *A. platensis*, *Chlorella vulgaris*, *Tetraselmis suecica*, and *Phaeodactylum tricornutum* (Table 1). Interesting results were obtained with a significant increase of antioxidant activity and phenolic compounds in supplemented cookies in comparison with control (cookies without microalga biomass incorporation). Regarding the physical properties, the incorporation of microalgae provided stable and innovative green colors that varied between a blueish-green (*A. platensis*) to a brownish-green (*P. tricornutum*). *Arthrospira platensis* provided a structuring effect on cookie texture being also responsible for the highest antioxidant activity values, protein and phenolic contents as well as the highest sensory scores (Batista et al. 2017). Another research work that studied the incorporation of an extract from *Haematococcus pluvialis*, a microalga extremely rich in astaxanthin, in cookies was able to achieve an improvement in their antioxidant capacity, nutritional profile, and phenolic content (Table 1). Furthermore, this food product revealed in vitro potential to lower the glycemic response of whole meal flour cookies (Hossain et al. 2017).

Foods enriched in omega-3 and omega-6 PUFA

The benefits associated with a balanced intake of omega-3 and omega-6 fatty acids in the prevention of several diseases, such as cancer, type 2 diabetes, inflammatory and cardiovascular diseases, ocular diseases, and arthritis, have been extensively reported in the scientific literature (Abel et al. 2014; Babuskin et al. 2014; Calder 2015; Shahidi and Ambigaipalan 2018; Innes and Calder 2020). This fact justifies why products incorporating such bioactive compounds have been in high demand in recent years (Babuskin et al. 2014). Babuskin et al. (2014) aimed to develop functional cookies and pasta incorporating the microalga *Nannochloropsis oculata* as a source of EPA and DHA omega-3 PUFA (Table 1). By incorporating 1% (w/w) of *N. oculata*, the authors achieved 98 and 63 mg $(100\ g)^{-1}$ of EPA and DHA, respectively, in cookies and pasta, creating two interesting functional products as a source of omega-3 fatty acids. Furthermore, firmness of cookies and pasta improved with addition of microalga biomass, and colors remained stable for 2 months of storage. Sensory evaluation by an untrained panel registered interesting results for both products: although cookies without microalgae biomass incorporation were preferred, cookies with 1 to 2% (w/w) of *N. oculata* were also appreciated and obtained a positive classification. Adding 3% (w/w) of microalgae resulted in a fishy taste which was reflected in a weak overall appreciation of the product especially regarding color and taste. For pasta, the same trend was observed but the panelists appreciated pasta with microalgae biomass incorporation up to 3% (w/w). These results help to understand that incorporating microalgae in different food matrices is translated in different aromas, flavors, textures, and appearances—important factors to consider along product development (Babuskin et al. 2014). *Dunaliella salina*, an edible green microalga, was also incorporated in pasta improving its nutritional content in minerals, phytochemicals and unsaturated fatty acids (Table 1, El-Baz et al. 2017).

Fermented foods

The development of fermented products such as yogurt or cheese with the introduction of algae constitutes an excellent opportunity to open a new segment of highly nutritional and healthy valued food products where a high number of lactic acid bacteria are duly combined with rich quantitative and qualitative profiles of natural bioactive metabolites (Ścieszka and Klewicka 2019). Spreadable processed cheese was used for the incorporation of *C. vulgaris* (2, 4, and 6% (w/w)) having achieved a high level of potassium, magnesium, selenium, zinc, and iron, and improved antioxidant potential (Tohamy et al. 2018). A fish jerky was used to incorporate *Sargassum wightii* (0, 3, and 5% (w/w)) with consequent increase in total dietary fiber, macro (protein and carbohydrates) and micronutrients (especially calcium and iron), and improved antioxidant and microbial properties (Hanjabam et al. 2017).

Another research aimed to develop a functional yogurt as a delivery vehicle for a *Pavlova lutheri* omega-3-rich lipid extract (Table 1). The addition of the extract did not affect the yogurt's general quality and increased the n-3 PUFA content of the product. In addition, the *P. lutheri* extract showed a potent anti-inflammatory activity in vitro, which can also benefit consumer health. Unfortunately, in terms of sensory evaluation, the results were not very promising registering poor consumer acceptability. Further research must address strategies to improve sensory quality of the product. This was the first study that addressed the incorporation of this microalgae into a carrier food such as yogurt, so certainly there will be opportunities for product improvement in the near future (Robertson et al. 2016). Similarly, Lane et al. (2014) aimed to test if nanoemulsion technology could improve the bioavailability of an omega-3-rich algal oil using yogurt as a food vehicle in comparison with bulk oil-enriched yogurt (Table 1). A single-blind randomized crossover trial was conducted with 11 subjects via administration of the two food products with a washout period of 21 days between interventions. Blood samples were taken for each intervention at baseline, 2, 4, 6, 24, and 48 h intervals. Yogurt with nanoemulsion incorporation revealed a significantly higher bioavailability percentage compared with control yogurt for n-3 PUFA giving preliminary results on the potential of nanoemulsion technology as a strategy to improve omega-3 fatty acids bioavailability in novel food products. As highlighted by the authors, products with vegetarian sources of n-3 PUFA are in high demand since vegetarians are short on recommended dietary guidelines. Such products could be part of the solution (Lane et al. 2014).

Food supplements

The risk of nutritional deficiencies and malnutrition is very common among the elderly populations due to appetite changes and reduced intake of minerals, vitamins, and protein. This unbalanced nutritional intake leads to progressively loss of strength, function, and muscle mass (a condition known as sarcopenia) that greatly influences the development of aging-related chronic diseases greatly raising morbidity and mortality among the elderly (Baum et al. 2016; Santos et al. 2016). Santos et al. (2016) aimed to develop a product with high nutritional value that could be useful as a supplement for the elderly population—a powdered chocolate flavor food with addition of 750 mg *A. platensis* per 100 g (Table 1). By adding this microalga, the authors achieved an interesting product source of protein and carbohydrates, with estimated 19 months of shelf life and with a good sensory acceptability by the target population (Santos et al. 2016). As highlighted by Figueiredo et al. (2016), functional foods could have an important role in increasing nutrient intake, via their adaptation to age-related nutritional and sensorial changes, and in decreasing the incidence of chronic debilitating diseases in the elderly.

Bread

Bread, a general commodity, is one of the most consumed foods in the world with an estimated reported consumption of 100 g per day in several countries such as Italy and Germany (Leclercq et al. 2009; Heuer et al. 2015; Angelino et al. 2017). Since this food comes in a lot of different shapes, textures, sizes, and sensory attributes, bread is a food product that is widely appreciated and, as such, a promising vehicle for functional ingredients from micro- and macroalgae (Angelino et al. 2017; Uribe-Wandurraga et al. 2019). Recently, functional breadsticks with considerable amounts of iron and selenium were successfully developed by incorporating the microalgae *C. vulgaris* and *A. platensis* (Table 1). In addition, the product revealed increased in color and texture stability over 15 days of storage (Uribe-Wandurraga et al. 2019). García-Segovia et al. (2017) aimed to evaluate the impact of adding the microalgae *Isochrysis galbana*, *T. suecica*, *Scenedesmus almeriensis* or *Nannochloropsis gaditana* on physico-chemical and texture properties of wheat bread (Table 1). The authors reported changes in color due the strong pigmentation of the algae, as well as in crust and crumb characteristics. Other parameters such as hardness, chewiness, and resilience were not modified by microalgae addition. Future studies should address consumer's acceptability of the product (García-Segovia et al. 2017). Similarly, addition of *C. vulgaris* up to 3.0 g per 100 g to wheat flour dough registered positive impacts on viscoelastic and rheology characteristics. In contrast, the addition of more than 3.0 g of *C. vulgaris* increased bread aging and impacted negatively on flavor, texture, and dough rheology (Table 1) (Graça et al. 2018). Microalgae have also been demonstrated to be an excellent choice for nutritional enhancement of bread. *A. platensis* was incorporated at 1 and 3% (w/w) leading to an increase in bread minerals, protein, and fat content. Bread with 1% (w/w) of this microalga was better appreciated since the addition of 3% (w/w) conferred a strong green tonality affecting the color negatively (Table 1) (Hafsa et al. 2014). Unfortunately, the incorporation of higher amounts of algae in bread has resulted in products with reduced acceptability regarding associated organoleptic properties. In this context, the color of the product seems to be the most relevant and reported factor, since it may easily influence negatively the sensory acceptability of the product. Future research should focus on overcoming these limitations.

Within the medical field framework, the effect of consuming bread with incorporated *Palmaria palmata* on the antioxidant potential, lipid profile, thyroid function, and inflammatory markers of healthy adults was analyzed (Allsopp et al. 2016). A randomized placebo-controlled intervention trial was conducted with two groups, i.e., 19 participants with control bread (without seaweed incorporation) and 20 participants with bread enriched with *P. palmata* (Table 1). The participants consumed 1 bread per day (230 g containing 5 g *P. palmata*) for 28 consecutive days. *Palmaria palmata*–enriched bread increased serum triglycerides, altered thyroid function (thyroid stimulating hormone was stimulated due to iodine content of seaweed), and stimulated inflammation (C-reactive protein increased—seaweed contains immunomodulatory heterosides such as floridoside that can be the trigger for such stimulation). It is also important to note that these physiological changes were unlikely to impact human health since clinical analyses registered all values in the normal physiological range (Allsopp et al. 2016). Further studies should focus on the functional components responsible for these physiological impacts in order to improve bioavailability of the functional compounds of *P. palmata* and consequently the quality of the final food product.

Soups

Soups are a good and convenient vehicle for the delivery of vitamins, minerals, phytochemicals, fiber, and water contributing to their recommended daily intake and subsequently to a healthy nutritional status. Their consumption also contributes to the maintenance of a balanced diet because, in general, they incorporate different kinds of plant-based foods (legumes, vegetables, tubers), and their fat content tends to be low (Galan et al. 2003). Given the high fiber and water contents, this food product has a powerful satiating effect and can help control daily energy intake (Galan et al. 2003). Soup is strongly enjoyed within certain cultures, for example it is imperative in the Portuguese gastronomic culture and heritage. According to Emílio Peres (1932–2003), a prominent figure in the medical and nutritional field in Portugal, "Soup is becoming fashionable and as such, it is on the track of current scientific research. It is recognized for its high value. Soup should be consumed by all including the rich, the stressed urbanite, the remedied, the countryfolk, the manual workers or even the idle. It is good for youth, adults and the elderly. Soup is part of the Portuguese tradition because it always has been, and will always be, useful for health." (Esteves et al. 2013).

In fact, soup is indeed on the track of scientific research, inclusively as a vehicle for marine resources enrichment. Lafarga et al. (2019) aimed to develop an innovative broccoli soup with addition of the microalgae *A. platensis*, *Chlorella*, or *Tetraselmis* (Table 1). By adding a range of 0.5 to 2.0% (w/v) of each microalga, the authors achieved different soups with good antioxidant capacity and higher concentration of bioaccessible polyphenols (ranging between 32.9 ± 1.1 and 45.6 ± 0.5 mg per 100 mL in a simulated gastrointestinal digestion model). Once again, soups formulated with lower contents of microalgae (0.5%) registered better acceptability indexes, which upholds the need to find incorporation strategies that may enable the inclusion of contents as high as possible to guarantee functionality without jeopardizing sensory quality (Lafarga et al. 2019). Similarly, a study performed in Brazil developed a dehydrated soup enriched with 15% (w/w) of *A. platensis* high in protein, fiber, lipids, chlorophyll content and improved antioxidant capacity (Table 1). This research, in particular, highlights the importance of microalgae incorporation strategy since even with a big percentage of *A. platensis* addition (15% w/w), the product registered good sensorial acceptability as well as high purchase intention (Los et al. 2018). Carrageenan (extracted from *K. alvarezii*) and agar (extracted from *Gracilaria verrucosa*)—two polysaccharides with thickening, gelling, and stabilizing properties—were combined in different percentages (4, 3, 2, 1% (w/w)) with 2.5 g (100 g)$^{-1}$ of the seaweed *U. lactuca* improving greatly the physical and nutritional properties of vegetable seaweed–based soup powder. It is worth highlighting the onset of a nutritional enhancement in several micronutrients such as calcium, potassium, magnesium, and iodine, for example in the soup formulated with 3 g of agar and 2.5 g (100 g)$^{-1}$ of seaweed, values of 53.39 ± 0.07 mg potassium (100 g)$^{-1}$, 45.8 ± 0.98 mg magnesium (100 g)$^{-1}$, and 250.56 ± 0.75 mg calcium (100 g)$^{-1}$ were achieved. This was indeed a tremendous achievement when compared with their comparative market soup which registered values of 5.6 ± 0.45 mg (100 g)$^{-1}$, 4.9 ± 0.32 mg (100 g)$^{-1}$, and 3.8 ± 0.23 mg (100 g)$^{-1}$, respectively. In addition, a large improvement of the product's apparent viscosity (highest reported values were 698 cups, 766 cups, and 951 cups) and considerable shelf life duration of 5 to 6 months under freezer storage (0 °C) were registered (Table 1) (Jayasinghe and Pahalawattaarachchi 2016). Another study also incorporated carrageenan from *K. alvarezii* in the development of a novel fish soup powder with nutritional enhancement especially in terms of mineral content (Table 1). Curiously, supplementation of carrageenan by 5% (w/w) did not affect consistency and flavor characteristics of the final product (Jeyakumari et al. 2016).

Olive oil, a highly recommended food within the Mediterranean diet given its cardiovascular protective properties and used as the main fat ingredient in soup preparation, has also been used as vehicle for incorporation of bioactive compounds derived from microalgae. Virgin olive oil was enriched with *Scenedesmus almeriensis* (carotenoid-rich extracts) at different concentrations (0.1 and 0.21 mg mL^{-1}); results demonstrated a nutritional enhancement of olive oil in beta-carotene and lutein, and improved overall quality of the final product (Table 1) (Limón et al. 2015).

Market innovations regarding products with microalgae and seaweeds

Consumer interest in products that combine health and nutrition and the increasing consciousness of the importance of finding new plant-based protein sources, that can reduce the environmental impact and the increasing demand of a growing and urbanized population, are driving people to search increasingly more for algae-based food products (Alexandratos and Bruinsma 2012; Buech 2018; Mintel 2018). Consequently, the market is adapting to this demand and although food products with algae are still in their infancy in Western countries, the number of foods and drinks containing algae doubled in the past few years according to the Mintel

Table 2 Industrially developed products with seaweeds and microalgae (product report provided by the Portugal Foods–Portuguese AgroFood Cluster) (Mintel 2018)

Type of food product	Country of origin	Commercial name	Algae incorporation (quantity)	Claims
Snack energy bar	Spain	Alguimya Luca Cranberry and Marine Microalgae Energy Bar	*Chlorella vulgaris* (0.5% w/w)	Gluten free, low/no/reduced allergen, vegan/ no animal ingredients, functional energy
Plant-based drink	France	Alter Eco Rice and Sorghum Drink with Calcium	*Lithothamnium calcareum* (n/a)	Added calcium, organic, vitamin/ mineral fortified, gluten free, low/no/reduced allergen, environmentally friendly product and package, ethical (human, charity, recycling, sustainable), ease of use
Seasonings	Sweden	Spicemaster Organic Herbal Salt with Natural Iodine	*Ascophyllum nodosum* (Kelp) (n/a)	No additives/preservatives, organic, vitamin/mineral fortified
	Germany	Maris Algen Pesto Seasoning Mix and Algae	Organic *Saccharina latissima* (n/a)	Organic, vegan/no animal ingredients
Pasta sauces	Germany	Bio-verde Fresh Vegan Algae Pesto	Unspecified algae (n/a)	Organic, ethical (human), vegan/no animal ingredients
Wet soup	Italy	DimmiSì Gusto d'Oriente Tokyo Style Soup	*Undaria pinnatifida* (Wakame) (n/a)	No additives/preservatives, high/added fiber, microwaveable, environmentally friendly product and package, ease of use, social media, ethical (recycling and sustainable)
Toasts	France	Algaé Gastronomie Seaweeeds Toasts	*Palmaria palmata* (Dulse), *Ulva* sp. (Sea lettuce), unspecified red algae) (n/a)	No information available
Pasta	Italy	Sottolestelle Bio Vegando Lentils, Red Seaweed and Thyme Wholegrain Fusilli Super Pasta	*Lithothamnion calcareum* (1% w/w)	High added fiber, organic, vegetarian, wholegrain, high/added protein, vegan/no animal ingredients, low/no/reduced saturated fat
	Spain	Gallo Nature Multi-vegetable Pasta with Spirulina, Turmeric and Beetroot	*Arthrospira platensis* (n/a)	All-natural product, high/ added fiber, functional (bone health, energy), convenient packaging
	France	Miss Algae Twist Pasta with Dulse, Nori, Wakame and Spirulina	*Palmaria palmata* (Dulse), *Porphyra* sp. (Nori, *Undaria pinnatifida* (Wakame) and *Arthrospira platensis* (n/a)	No information available
Rice	France	Miss Algae Seaweed Rice	*Palmaria palmata* (Dulse), *Ulva sp.* (green laver), *Porphyra* sp. (Nori) (n/a)	No information available
Savory biscuits/-crackers	Spain	Gullón Vitalday Oat and Rice Cakes with Spirulina	*Arthrospira platensis* (n/a)	No information available
	Austria	Helga Sea Salt Algae Crackers	*Chlorella vulgaris* (n/a)	Organic, on-the-go, vegan/no animal ingredients
Sweet biscuits/-cookies	France	Super Green Me Spirulina Mini Cookies with Cranberry	*Arthrospira platensis* (n/a)	Organic
Prepared meals	Spain	Carlota Organic Chickpeas Stew with Kombo Algae	*Laminaria japonica* (Kombu) (n/a)	Organic, gluten free, low/no/reduced allergen, ease of use, vegan/no animal ingredients, low/no/reduced saturated fat
		Gerblé 100% Vegetal Quinoa with Vegetables	Unspecified algae (n/a)	No additives/ preservatives, high/ added fiber, microwaveable, organic
Chocolate tablets	Germany	Algenheld Vegan Algae Chocolate	*Arthrospira platensis* (5 g)	No additives/ preservatives, organic, vegan/no animal ingredients, social media
Baking ingredients and mixes	France	La Mandorle Brunche Preparation Mix	*Lithothamnium calcareum* and unspecified organic brown algae (n/a)	Organic, gluten free, functional (bone health, brain, and nervous system, energy), low/no/reduced allergen, environmentally friendly package, ease of use, vegan/no animal ingredients, low/no/reduced lactose, recycling, dairy-free
Meat substitutes	Netherlands	Olijck Olicke Henry Sea Vegetable Burguer with Lentils, Mushroom and Onion	*Undaria pinnatifida* (Wakame) (n/a)	Gluten-free, low/no/ reduced allergen, low/no/reduced lactose, social media

n/a, not available

database (Mintel 2018). From this total, snacks and juice drinks are the most launched categories of food products with algae, registering between October 2016 and September 2017 approximately 16% and 11% increase, respectively (Mintel 2018). In what concerns the percentage of new products featuring algae market launches in 2018, sugar and gum confectionery (34.5%), bakery (10.9%), meals (10.9%), and chocolate confectionery (10.6%) were the most prevalent (Mintel 2018). The most used algae-based ingredients between 2017 and 2018 were *A. platensis* concentrate (46.1%), unspecified algae (19.1%), *A. platensis* (10.6%), *A. platensis* extract (6.5%) and *Porphyra* sp. (nori) (4.9%) (Mintel 2018). The use of these new ingredients makes several claims possible where environmentally friendly package (23.5%), no additives/preservatives (22.1%), recycling (19.6%), and organic (17.8%) stand out as the mostly used in 2018 (Mintel 2018). As previously highlighted, environmental sustainability is an imperative tendency, aligned with Health and Food Authorities Sustainable Development Goals (Food and Agriculture Organization 2015) to which market and consumers are clearly adapting and adhering as reflected in such increased number of product launches, indeed, the top product claims in these food products are clearly environmentally related ones. As previously demonstrated, the overwhelming novelty of seaweeds and microalgae in their role to add extra value to food products has been documented in the scientific literature especially over recent years. Nevertheless there are limited published data available on the nutritional composition of the several products that reach the market; these have not been scientifically documented. This review aims to narrow this gap by providing updated information on products, algae content, and potential claims. Table 2 lists several industrially developed products worldwide with incorporated seaweeds and microalgae with interesting added value to satisfy increasing consumer demands.

Based on the abovementioned rationale, different product categories are being increasingly sought for incorporation of edible seaweeds and microalgae. Nutritional, functional, and environmental benefits have been highlighted. Nevertheless, producers and food manufacturers continue to face important challenges. Algal producers using land-based cultivation systems need to guarantee standardized products in terms of nutrient and phytochemical contents. It is well-known that seaweed species vary greatly in their protein content dependent on such factors as season and environmental growth conditions; the same applies to pigments or bioactive compounds with antioxidant potential for example. Furthermore, safety issues need to be continuously accounted for, not only in terms of microbiological quality of raw materials but also in terms of excessive salt, iodine, and heavy metal content including arsenic species (Freitas and Gomes 2019). Legislative measures are imperative to guarantee proper monitoring programs, correct labeling of food products, and establishment of safe portion sizes (Cherry et al. 2019; van der Spiegel et al. 2013). A very recent review provides enlightment on the required fields needed and potential strategies associated to be developed in the near future if seaweeds and microalgae are to contribute to future global food security (van der Spiegel et al. 2013; Cherry et al. 2019). Solutions may include more objective legislative measures and safety cut-offs, the use of improved technologies that may destroy/remove possible contaminants, the generation of more mechanistic evidence to uphold health claims, and the need for more human intervention studies required to substantiate nutritional and functional benefits of nutrients and bioactive compounds found in the different algae (Cherry et al. 2019).

Conclusions

Seaweeds and microalgae are excellent sustainable marine resources to be incorporated as ingredients in the development of innovative food products that privilege health, nutrition, and environmental sustainability. Despite the clear steady growth of scientific and industrial interests in food products with seaweeds and microalgae, fueled by increasing consumer demand, further investments in applied product development science and background mechanistic science are imperative especially in what concerns technologies that could optimize product safety and sensory characteristics without sacrificing the optimal quantity of marine ingredient that could bring about health and nutritional benefits. Legislative measures related with proper monitoring programs, labeling procedures, and good manufacturing practices are essential to prevent any biological/chemical hazards that may jeopardize a safe and beneficial product development. Furthermore, future works must focus on analyzing the bioaccessibility and bioavailability of marine bioactive compounds, especially when these ingredients are incorporated in different food matrices, a driving factor of such important nutritional and health benefits. These data are essential to optimize product development and effectively create food products that could work as preventive or adjuvant therapeutic strategies against the burden of chronic and debilitating noncommunicable diseases in today's society.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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