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Algae as nutritional and bioactive food ingredients

Las algas como ingredientes nutricionales y bioactivos de alimentos

G. Díaz-Godínez[1]*, K. Peña-Solis[1], G. Díaz-Domínguez[2]
[1]*Research Center for Biological Sciences, Autonomous University of Tlaxcala, Tlax., Mexico.*
[2]*Metropolitan Autonomous University Iztapalapa, CDMX, Mexico.*
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Abstract

Humanity currently presents many challenges, among which efficient food production is one of the greatest, which is why research is carried out to find unconventional protein sources. A potential alternative is algae (unicellular or multicellular), which generally develop in aquatic environments, whether in fresh or salt water, with the characteristic that they carry out photosynthesis. These organisms have various colors due to their pigments such as chlorophyll, phycocyanin, carotene, fucoxanthin, among others. Although the consumption of algae is very old, special attention has currently been paid to their nutritional quality since they show a high concentration of minerals, vitamins and proteins with low caloric and lipid content, and have also shown antibacterial, antifungal, antiviral, antioxidant, antihypertensive, immunomodulatory, anticancer, hepatoprotective, anticoagulant activities, among others, which is why they are considered functional or nutraceuticals foods. Algae have been present in the cuisine of many cultures. New food products have also been developed where algae or some of its components are used as ingredients for their functional and/or nutraceutical properties. In this review, some nutritional and functional properties of some algae are mentioned, as well as research where foods added either with algae or some of their components have been developed.
Keywords: Algae, functional foods, microalgae, nutraceutical foods, seaweeds.

Resumen

La humanidad actualmente presenta muchos desafíos, entre los cuales la producción eficiente de alimentos es uno de los más grandes, por lo que se realizan investigaciones para encontrar fuentes de proteínas no convencionales. Una potencial alternativa son las algas (unicelulares o multicelulares), que generalmente se desarrollan en ambientes acuáticos, ya sea en agua dulce o salada, con la característica de que realizan la fotosíntesis. Estos organismos presentan varios colores por sus pigmentos como clorofila, ficocianina, caroteno, fucoxantina, entre otros. Aunque el consumo de algas es muy antiguo, actualmente se ha prestado especial atención a su calidad nutricional ya que muestran una alta concentración de minerales, vitaminas and proteinas con bajo contenido calórico y lipídico, además han mostrado propiedades antibacterianas, antifúngicas, antivirales, antioxidantes, antihipertensivas, inmunomoduladoras, anticancerígenas, hepatoprotectoras, anticoagulantes, etc., por lo que se consideran alimentos funcionales o nutracéuticos. Las algas han estado presentes en la cocina de muchas culturas, también se han desarrollado nuevos productos alimenticios donde las algas o alguno de sus componentes se utilizan como ingredientes por sus propiedades funcionales y/o nutracéuticas. En esta revisión se mencionan algunas propiedades nutricionales y funcionales de algunas algas, así como investigaciones donde se han desarrollado alimentos adicionados ya sea con algas o alguno de sus componentes. Algas, alimentos funcionales, microalgas, alimentos nutracéuticos, algas marinas.
Palabras clave: Algas, alimentos funcionales, microalgas, alimentos nutracéuticos, algas marinas.

*Corresponding author. E-mail: diazgdo@hotmail.com; gerardo.diaz@uatx.mx ;
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1 Introduction

Algae, whether microalgae or seaweeds, have been consumed by humans since ancient times, and are currently a focus of study due to their high nutritional quality and the biological activities they present. Much research is being carried out to describe their nutraceutical properties and their potential use in the design of new food products. There are reports on their use as a food or ingredient in food processing, but their metabolites have also been used in both the food and pharmaceutical industries; to mention some algae-based products are energy bars, breads, cookies, cereals, desserts, ice creams, pastes and emulsions, etc., in addition, algae powders and extracts are available in tablets, capsules, crystals, gels and dietary supplements (Rao and Ravishankar, 2018).

1.1 Algae

Algae are organisms that are somewhat difficult to define, however, it can be said that they are generally aquatic and autotrophic through photosynthesis, although they are not higher plants. They are eukaryotic organisms, although there are prokaryotes such as cyanobacteria and there are cases of symbiosis between eukaryotic cells and a photosynthetic cyanobacterium (Raven and Giordano, 2014). Some authors include all the algae within the Protista kingdom, others, for their part, only include unicellular algae and green algae (chlorophytes) in this group, while the rest of the multicellular algae include them in the plant kingdom (Raven and Giordano, 2014). Depending on their size, microalgae are unicellular and microscopic, while multicellular ones can measure many meters in length and are known as macroalgae or marine algae (Figueiredo *et al*., 2016). There are three main classes of marine algae based on their pigmentation: Rhodophyta (Red seaweed), Phaeophyceae (Brown seaweed) and Chlorophyta (Green seaweed) (Biris-Dorhoi *et al*., 2020), as well as blue-green algae (cyanobacteria/Cyanophyta), which are the largest prokaryotic and capable of forming colonies.

Rhodophyta. Red algae or Rhodophyta are almost exclusively marine, constituting the largest and most diversified group of tropical reef plants. They present a great diversity of forms, they exist as forms of small filamentous grasses, or of large and beautiful coral reef organisms. These algae have large amounts of phycoerythrin (water soluble), which is a red pigment that, when present together with other pigments in photosynthetic cells, produces colors such as pale pink, purple, iridescent blue, etc. The vast majority of red algae are macroscopic, multicellular, and reproduce sexually (Littler *et al*., 1983).

Phaeophyceae. Brown algae or Phaeophyceae contain large amounts of fucoxanthin, which is the brown pigment, although they also contain significant amounts of alginic acid and fucoidin. These organisms are macroalgae that during their development present a multicellular organization, generating differentiated tissues and producing flagellated spores for their reproduction. They have cellulose in their cell walls, most of these algae have microscopic hair-like structures on their surface that they use in absorbing nutrients (Littler *et al*., 1983).

Chlorophyta. Green algae or chlorophytes, present chlorophyll and are predominantly green, although they also contain carotenoids and xanthophylls. These algae are considered the ancestors of vascular plants, as they contain these same basic pigments. These algae can be microscopic in size, filamentous or in thin sheets, they can be spongy, gelatinous, leathery or brittle and can measure more than 1.5 m in length. They store their energy reserves in the form of starch, all produce spores and flagellate gametes. The common habitat of green algae is tropical coral reefs and at the bottom of lagoons, which may be interspersed with seagrass sprouts (Littler and Littler, 1994). Several green algae of the filamentous or lamellar type resist stressful conditions and can be considered indicators of recently disturbed areas.

Cyanobacteria (Blue-green algae). The algae in this group are prokaryotic and are not part of true plants. Cyanobacteria are considered to be a very old group and was the first group to develop aerobic photosynthesis. These algae show colors ranging from pink to purple and black, which are the result of a combination of red, blue and green colors provided by the pigments phycoerythrin, phycocyanin and chlorophyll, respectively. Several cyanobacteria also produce hormogonia, which are reproductive filaments that leave the original colony to generate new colonies. The biomass of some cyanobacteria is detrimental to human health and coral reefs, due to the production of some metabolites that present toxicity to many organisms including invertebrates, plankton and fish (Ruetzler *et al*., 1983). Some cyanobacteria are dangerous to humans and animals as they produce endotoxins, neurotoxins, cytotoxins and hepatotoxins (Paul *et al*., 2007). It is important to mention that cyanobacteria are the only organisms capable of reducing carbon and nitrogen in aerobic environments, which may be a characteristic that influenced their ecological and evolutionary success in certain coral reef habitats. Blue-green algae are abundant all over the world, they can withstand various extreme conditions, such as severe drought, bright sun and intense heat, rain, high salinity, etc. Cyanobacteria are among the oldest species known on Earth (Littler and Littler, 2013).

1.2 Algal nutritional components

Algae are a very abundant and important natural resource within food chains, impacting ecosystems due to their consumption of CO_2 and inorganic nutrients that, in the presence of sunlight, produce oxygen and biomass. Its chemical composition represents an excellent source of nutrients that include proteins, amino acids, vitamins (A, B1, B2, B6, niacin and C), minerals, lipids, fatty acids, carbohydrates, nucleic acids and pigments, among others (Pawar *et al*., 2022).

Seaweeds and microalgae are an important source of protein, although their content varies depending on the species of algae, the season of the year and the general conditions in which they develop (Solis-Méndez *et al*., 2020); however, their content is high and, on many occasions, they present most of the essential amino acids, resembling the quality of proteins from animal sources (Wang *et al*., 2021). The reported dry weight crude protein content of microalgae biomass varies from 6 to 70%, however, most report values around 40% (Becker, 2007; Chacón-Lee and González-Mariño, 2010). The crude protein content on a dry basis has been reported for several algae. Table 1 shows the values reported for some of them, however, it is important to mention that protein content values can vary even between individuals of the same species, which may be due to the type and concentration of nutrients, the environmental conditions where the algae develop, the conditions and methods of analysis, among others. For example, in *Arthrospira maxima* the values are 56-71% (Oliveira *et al*., 1999; Milledge, 2011; Peña-Solis *et al*., 2023), in *Arthrospira platensis* the values vary from 55-70% (Oliveira *et al*., 1999; Becker, 2007; Habib *et al*., 2008; Niccolai *et al*., 2020), in *Chlorella vulgaris* the values are between 51-58% (Becker, 2007; Tibbetts *et al*., 2015). There are species that were reported very large variations in their crude protein content, such as *Euglena gracilis* with values of 39-61% (Becker, 2007), *Nannochloropsis granulata* presented contents between 18-34% (Tibbetts *et al*., 2015), and Spirogyra sp. showed 6-20% (Becker, 2007).

Table 1 also shows values of the lipid content of some algae; many species produce lipids in considerable quantities, in some cases reaching up to 40-70% of their dry weight, as is the case with *Schizochytrium* sp., *Chlorella* sp. and *Nannochloropsis* sp. (Chisti, 2007; Georgianna and Mayfield, 2012; Bellou *et al*., 2014). The content of saturated, monounsaturated and polyunsaturated fatty acids (PUFA) in algal lipids is a topic of great interest. It can be said that cyanobacteria and green algae (Chlorophyta and Streptophyta) contain low amounts of fatty acids, predominantly saturated and monounsaturated, as well as, small amounts of PUFAs, while Chromalveolata algae contain large amounts of PUFAs (Lang *et al*., 2011). There are reports on the production of linoleic and α-linoleic acid by *Spirulina* spp. (Chaiklahan *et al*., 2008; Sahu *et al*., 2013). *Chaetoceros* gracilis produces oleic acid, palmitic acid, linoleic acid, α-linolenic acid, arachidonic acid, docosahexaenoic acid and eicosapentaenoic acid. *Phaeodactylum tricornutum* contains eicosapentaenoic acid, palmitoleic acid, palmitic acid, hexadecatrienoic acid and myristic acid (Villarruel-López *et al*., 2017). Recently, in a bibliographical review, the content of fatty acids and PUFAs (16:0, 16:1, 18:1, n6-18:2, n3-18:3, n6-20:4, n3-20:5, n3-22:6) of some species of algae was mentioned, within which are included *Chlamydomonas reinhardtii*, *Dunaliella salina*, *Scenedesmus obliquus*, *Chlorella vulgaris*, *Lauderia borealis*, *Phaeodactylum tricornutum*, *Nannochloropsis gaditana*, *Emiliania huxleyi*, *Pavlova lutheri*, *Ectocarpus siliculosus*, *Fucus vesiculosus*, *Chondrus crispus*, *Porphyridium purpureum* (Harwood, 2019). Ohse *et al*. (2015), reported the lipid content and fatty acid profiles of nine marine species (*Nannochloropsis oculate*, *Thalassiosira pseudonana*, *Phaeodactylum tricornutum*, *Isochrysis galbana*, *Tetraselmis suecica*, *Tetraselmis chuii*, *Chaetoceros muelleri*, *Thalassiosira fluviatilis* and *Isochrysis* sp.) and one freshwater microalga (*Chlorella vulgaris*), cultured *in vitro*. Fatty acid composition of each lipid component of the alga *Scenedesmus obliquus* was also reported (Choi *et al*., 1987).

Table 1 shows the carbohydrate content of some algae. The carbohydrate content can vary depending on the species of algae as well as the environmental conditions in which they grow, but in general, the carbohydrate content is less than that of proteins and in many cases also less to lipid content (Villarruel-López *et al*., 2017). Among the carbohydrates present in algae are monosaccharides such as glucose, rhamnose, xylose, mannose, among others, as well as, some disaccharides, oligosaccharides, and polysaccharides. Cyanobacteria do not have cellulose in their cell wall, *Arthrospira platensis* has a cell wall rich in murein, and they have intracellular glycogen granules; some eukaryotic microalgae have cellulose in their cell wall (Safi *et al*., 2014). In red algae, cellulose and mucilages such as agar or carrageenan are found in their cell walls and they store starch and glycogen. In brown algae, water-soluble β-1,3-glucans have been found as storage polysaccharides. Green microalgae have cellulose in their cell wall and starch (amylose and amylopectin) as a storage carbohydrate (Villarruel-López *et al*., 2017).

Since algae are photosynthetic organisms, they contain pigments that are classified as chlorophylls (0.5-1.0% of dry weight), phycobilins (until 8% of dry weight) and carotenoids (carotenes and xanthophylls;

Table 1. Protein, carbohydrate and lipid content of some algae.

Algae	Protein	Lipids	Carbohydrates	References
	Content (g/100g)			
Acutodesmus dimorphus	28.1	18.8	38.6	Tibbetts *et al*., 2015
Arthrospira maxima	57	6	15	Peña-Solis *et al*., 2023
Arthrospira platensis	55.8	14.2	22.2	Tibbetts *et al*., 2015
Botryococcus braunii	39-40	25-34	19-31	Tibbetts *et al*., 2015
Chaetoceros calcitrans	34	16	6	Brown, 1991
Chaetoceros calcitrans	40	23	37	Velasco *et al*., 2016
Chaetoceros gracilis	12	7.2	4.7	Brown, 1991
Chaetoceros muelleri	59	31	10	Velasco *et al*., 2016
Chlamydomonas reinhardtii	48	21	17	Becker, 2007
Chlorella pyrenoidosa	57	2	26	Chisti, 2007
Chlorella vulgaris	53.3	15.7	25.2	Tibbetts *et al*., 2015
Dunaliella primolecta	12	-	-	Slocombe *et al*., 2013
Dunaliella salina	57	6	32	Becker, 2007
Dunaliella sp.	34.17	14.36	14.57	Kent *et al*., 2015
Dunaliella tertiolecta	11	-	-	Barbarino and Lourencço, 2005
Isochrysis galbana	27	11	34	Gorgônio *et al*., 2013
Nannochloropsis granulata	18-34	24-48	27-36	Tibbetts *et al*., 2015
Nannochloropsis sp.	30	22	10	Kent *et al*., 2015
Neochloris oleoabundans	30.1	15.4	37.8	Tibbetts *et al*., 2015
Nitzschia closterium	26	13	9.8	Brown, 1991
Pavlova sp.	24-29	9-14	6-9	Brown, 1991; Becker, 2007
Phaeodactylum tricornutum	39.6	18.2	25.2	Tibbetts *et al*., 2015
Porphyridium aerugineum	31.6	13.7	45.8	Tibbetts *et al*., 2015
Porphyridium cruentum	28-39	9-14	40-57	Becker, 2007
Prymnesium sp.	28-45	22-38	25-33	Ricketts, 1966
Scenedesmus obliquus	48-56	12-14	10-17	Becker, 2007; González-López *et al*., 2010
Scenedesmus sp.	31	15	28	Kent *et al*., 2015
Schizochytrium sp.	-	50-77	-	Chisti, 2007
Skeletonema costatum	25	10	4.6	Brown, 1991
Spirulina maxima	60-71	6-7	13-16	Becker, 2007
Synechococcus sp.	63	11	15	Becker, 2007
Tetraselmis chuii	46.5	12.3	25	Tibbetts *et al*., 2015
Tetraselmis sp.	36-52	16-45	15-24	Brown, 1991; Schwenzfeier *et al*., 2011
Thalassiosira pseudonana	34	19	8.8	Brown, 1991
Ulva lactuca	8.44	5.79	25.81	Chakraborty and Santra, 2008

usually 0.1-0.2% of dry weight, but achieving up to 14% in some species). Among the algae mostly used to produce pigments are *Chlorella vulgaris* (chlorophylls), *Arthrospira platensis* (phycocyanin), *Dunaliella salina* (β-carotene) and *Haematococcus pluvialis* (astaxanthin) (Silva *et al*., 2020).

1.3 Bioactive properties of algae

The lifestyle that the world population currently presents has led us to have bad eating habits and coupled with little physical activity, the number of chronic diseases has increased, for which there is much research for the development of new treatments and medications, including bioactive compounds. These compounds with biological activity are a focus of much attention, looking for the producing organisms, as well as, the conditions of maximum production, without neglecting the understanding of their mechanisms of action. Algae are organisms that have been shown to produce a wide variety of compounds with biological activities. Among the bioactive compounds found in algae are lipids, polyphenols, polysaccharides, proteins and peptides, sterols, flavonoids, alkaloids, pigments, etc. (Peñalver *et al*., 2020). Due to the presence of nutrients and bioactive compounds, algae are considered as nutraceuticals or functional foods. The terms "nutraceutical foods" or "functional foods" are not legally recognized in many parts of the world, and some authors consider them synonymous. However, functional foods can generally be defined as products that, when ingested, in addition to nutrients provide health benefits including the prevention and treatment of diseases, while nutraceuticals are foods added with compounds with biological activity or products

Table 2. Biological activities present in some algae.

Biological activity	Compound/extract	Algae	References
Anticancer	Glycoproteins	*Laminaria japonica*	Go *et al*., 2010;
	Fucoindans	*Sargassum hornery, Ecklonia cava, Costaria costata*	Ermakova *et al*., 2011
	Heterofucans	*Sargassum filipendula*	Costa *et al*., 2011
	Squalene-derived	*Laurencia viridis*	Lahaye and Robic, 2007
	Phlorotannins	*Ecklonia cava*	Kong *et al*., 2009
	Astaxanthin	*Dunaliella salina*	Balasubramaniam *et al*., 2021
	β-carotene	*Hamatococcus pluvialis*	
	Lutein	*Chlorella vulgaris*	Cha *et al*., 2008
	Violaxanthin	*Dunaliella tertiolecta*	Pasquet *et al*., 2011
	Fucoxanthin	*Phaeodactylum tricornutum*	Neumann *et al*., 2019
	Phycocyanin	*Spirulina platensis*	Deniz *et al*., 2016; Prabakaran *et al*., 2020
	Cis β-carotene	*Dunaliella bardawil*	Harari *et al*., 2013
	Aqueous and ethanolic extracts	*Gracilaria corticate, Sargassum oligocystum*	Veluchamy and Palaniswamy, 2020.
	Methanolic and ethanolic extracts	*Gracilaria tenuistipitata, Plocamium telfairiae*	
Antiviral	Cyanovirin	*Nostoc ellpsosporum*	Boyd *et al*., 1997
	Scytovirin	*Scytonema varium*	Bokesch *et al*., 2003
	Sulfated polysaccharides	*Spirulina platensis, Porphyridium cruentum*	Mader *et al*., 2016, Huleihel *et al*., 2001
	Fucans	*Dictyota mertensii, lobophoravariegata, Spatoglossum schroederi, Fucus vesiculosus*	Queiroz *et al*., 2008
Antimicrobial	Extracts (methanol/toluene; 3:1)	*Ulva fasciata, Bryopsis plumosa, Chaetomorpha antennina, Acrosiphonia orientalis, Sargassum wightii, Grateloupia filicina, Hypnea pannosa, Gracilaria corticate Portieria hornemannii, Cheilosporum spectabile, Centroceras clavulatum, Chnoospora bicanaliculata, and Padina tetrastromatica*	Shanmughapriya *et al*., 2008; Prarthana and Maruthi, 2019
	Methanol extracts	*Dunaliella salina Pseudokirchneriella subcapitata*	Pane *et al*., 2015
	Diethyl ether extracts	*Ulva rigida, Enteromorpha linza, Cystoseira mediterranea, Ectocarpus siliculosus, Gracilaria gracilis*	Tuney *et al*., 2006
	Ethanolic extract	*Dictyota linearis*	
Antioxidant	Fucoidan	*Fucus vesiculosus*	Rocha de Souza *et al*., 2007
	Phlorotannins	*Ecklonia cava*	Li *et al*., 2009
	Sesquiterpenoids	*Ulva fasciata*	Chakraborty and Paulraj, 2010
	Flavonoids	*Ulva latuca*	Meenakshi *et al*., 2009
		Gracilaria dendroides	Al-Saif *et al*., 2014
	Anthraquinones, Coumarins, Phycobiliproteins, Flavonoids, Carotenoids, Chlorophylls	Various microalgae and seaweeds	Martínez-Palma *et al*., 2015; Biris-Dorhoi *et al*., 2020; Veluchamy and Palaniswamy, 2020; Peña-Solis *et al*., 2023.

in the form of capsules, pills or liquid extracts presenting the biological properties (Shahidi, 2012; Bagchi, 2006; Hafting *et al*., 2012). Interest in algae as nutraceuticals or functional foods has increased recently, as many biological activities have been observed. Table 2 lists some algae and the compounds that have shown anticancer, antiviral, antimicrobial and antioxidant activity. Although other biological activities have been reported in algae such as anti-inflammatory, anti-obesity, neuroprotective, anti-diabetic, anticoagulant, anti-aging, reduction of blood pressure and fat, antithrombotic, antidepressant and anti-fatigue properties, anti-allergic effect, immunomodulatory activity, neuroprotective effect, among others (Figueiredo *et al*., 2016; Biris-Dorhoi *et al*., 2020; Veluchamy and Palaniswamy, 2020; Pawar *et al*., 2022).

2 Algal-based functional/nutraceutical foods

The research and development of pharmaceutical technologies as well as in the area of health have favored an increase in the life expectancy of the human being, however, the sedentary lifestyle and bad eating habits have generated an increase in the population but with many chronic-degenerative ailments. In this sense, one of the challenges we face is to produce more and better food but in the same existing spaces. It is important to consider underexploited sources such as algae, since as mentioned above, they are organisms with excellent nutritional quality and also with biological properties that would provide health benefits for those who consume them.

It is not known exactly when algae began to be consumed, however, there are records that they have been part of the human diet for approximately 14,000 years BP (Dillehay *et al*., 2008) and there is evidence of their consumption in China 300 A.D. (Wells *et al*., 2017). There are also records that the *Spirulina* alga (*Arthrospira maxima*) produced in Lake Texcoco, Mexico, was consumed by the Aztec culture in the form of a small dry cake which they called "Tecuitlatl" (Ciferri, 1983). *Spirulina* used as human food also has a long history among the Kanembu tribes that live around Lake Chad in the Republic of Chad (Qian, 2004). Algae are consumed as a main dish or as an ingredient in food preparation, but there are also some components extracted from algae that, due to their techno-functional properties, favor the design and development of new food products. It is worth noting in Asian food, the use of nori (Porphyra spp.) for making sushi and sea lettuce (*Ulva lactuca*), wakame (*Undaria pinnatifida*), kombu (*Saccharina japonica*), and also Irish moss (*Chondrus crispus*) and thongweed or sea spaghetti (*Himanthalia elongate*), are eaten (Matos *et al*., 2022). Among the foods added with algae are fish, meat, dairy analogues, pasta, bread, etc. (Matos *et al*., 2022; Onwezen *et al*., 2021), and within the compounds extracted from algae with techno-functional properties we can mention polysaccharides such as carrageenan, alginate and agar-agar that are used as thickening agents for beverages, ice creams and as gelling agents for jellies (Hung *et al*., 2021). Microalgae are also used to enhance the flavor and texture of food (Coleman *et al*., 2022). Among the species of algae with potential use as food or as a food ingredient, some microalgae can be mentioned, such as *Botryococcus* sp., *Chaetoceros* sp., *Chlorella* sp., *Crypthecodinium* sp. *Dunaliella* sp., *Haematococcus* sp., *Isochrysis* sp., *Nannochloris* sp., *Nitzschia* sp., *Phaeodactylum* sp., Porphyridium sp., *Schizochytrium* sp., Skeletonema sp. *Spirulina* sp., *Tetraselmis* sp. (Sathasivam *et al*., 2019; Hu *et al*., 2018), and some seaweeds can also be mentioned, such as *Acanthophora nayadiformis*, *Agarum clathratum*, *Ascophyllum nodosum*, *Bifurcaria bifurcata*, *Botryocladia wrightii*, *Canistrocarpus cervicornis*, *Chondracanthus chamissoi*, *Dictyota bartayesiana*, *Durvillaea antarctica*, *Ecklonia cava*, *Egregia menziesii*, *Eisenia arborea*, *Fucus* spp., *Gelidiella acerosa*, *Gracilariopsis lemaneiformis*, *Halimeda macroloba*, *Halymenia durvillei*, *Hypnea musciformis*, *Lessonia nigrescens*, *Lessonia trabeculata*, *Lobophora variegata*, *Macrocystis pyrifera*, *Mazzaella canaliculata*, *Nizamuddinia zanardinii*, *Osmundaria obtusiloba*, *Phaeodactylum tricornutum*, *Polyopes affinis*, *Sargassum cinereum*, *Sargassum confusum*, *Sargassum cristaefolium*, *Sargassum fusiforme*, *Sargassum hemiphyllum*, *Sargassum horneri*, *Sargassum wightii*, *Turbinaria decurrens*, *Ulva lactuca*, *Ulva linza*, *Ulva prolifera*, *Ulva reticulata* (Choudhary *et al*., 2021).

The design and production of algae-based foods has recently increased, it is estimated that worldwide between 2015 and 2019 an amount of 13090 products with algal biomass or some algal derivative were reached, where dairy products, desserts and ice creams were the most abundant (Boukid and Castellari, 2021). Despite the large number of existing products, research continues seeking the development of new foods with the nutritional and biofunctional benefits of algae. Table 3 shows a list of some algae or products derived from algae used in food formulation, and below are some scientific studies describing the techno-functional properties of algae and their application in the design and production of foods.

The microalgae *Arthrospira platensis* and *Chlorella vulgaris* were used as ingredients for 3D printing cookie dough, achieving greater mechanical resistance and elasticity, favoring the 3D printing process of cookies, making them more stable and resistant to baking (Uribe-Wandurraga *et al*., 2021). The microalga rich in astaxanthin "*Haematococcus pluvialis*" was dehydrated and pulverized to be used in the preparation of wholemeal cookies. Up to 15% of the whole grain flour was replaced by powder of the alga rich in astaxanthin. It was possible to reduce the release of glucose during the *in vitro* digestion of the cookies and a high content of astaxanthin was observed with an increase of the amount of phenolic compounds and antioxidant activity (Hossain *et al*., 2017). Sea grape (*Caulerpa racemosa*) was incorporated into cookies; the alga increased the water and oil absorption capacity of the flour mixture as well as the retention capacity of other ingredients such as sodium carbonate, lactic acid and sucrose. The content of phenolic compounds and their antioxidant activity increased, the protein and fiber content were higher and the acceptability was adequate (Kumar *et al*., 2018).

Table 3. Some algae used in food processing.

Food group	Specific food	Algae	References
Dairy	Yogurt	*Chlorella* sp.	Cho *et al*., 2004
		Pavlova lutheri	Robertson *et al*., 2016
		Spirulina platensis	Bchir *et al*., 2019; Khaledabad *et al*., 2020
		Isochrysis galbana	Matos *et al*., 2021
	Probiotic fermented milks	*Spirulina platensis, Chlorella vulgaris*	Beheshtipour *et al*., 2013
	Functional fermented dairy products	*Spirulina platensis*	Varga *et al*., 2002; Molnár *et al*., 2005
	Ice cream	*Diacronema vlkianum, Porphyridium cruentum, Nannochloropsis oculata*	Durmaz *et al*., 2020
		Spirulina platensis	Agustini *et al*., 2016; Tiepo *et al*., 2021
	Processed cheese	*Spirulina maxima*	Mohamed *et al*., 2020
		Chlorella sp.	Jeon, 2006
	Bacteriologically acidified feta-type (BAF) cheese	*Spirulina platensis*	Golmakani *et al*., 2019
	Soft cheese		Agustini *et al*., 2016
	Greek soft cheese		Bosnea *et al*., 2020
	Spreadable processed cheese	*Chlorella vulgaris*	Tohamy *et al*., 2018
Bakery	Pizza and chocolate cake	*Spirulina* sp.	Khafagy *et al*., 2023
	Bread	*Dunaliella* sp.	Finney *et al*., 1984
		Microchloropsis gaditana, Tetraselmis chuii, Chlorella vulgaris	Qazi *et al*., 2021
		Arthrospira platensis, Chlorella vulgaris	Sukhikh *et al*., 2022
		Arthrospira fusiformis	Achour *et al*., 2014
		Arthrospira platensis	Ak *et al*., 2016
		Arthrospira sp.	Dinu *et al*., 2012
		Isochrysis galbana,Tetraselmis suecica, Scenedesmus almeriensis Nannochloropsis gaditana	Garcia-Segovia *et al*., 2017
	Gluten free bread	*Arthrospira platensis*	Figueira *et al*., 2011
	Extruded snacks	*Arthrospira* sp.	Lucas *et al*., 2018
	Biscuits	*Isochrysis galbana*	Gouveia *et al*., 2008b
		Arthrospira platensis	Baky *et al*., 2015; Singh *et al*., 2015
		Arthrospira platensis, Chlorella vulgaris Tetraselmis suecica, Phaeodactylum tricornutum	Batista *et al*., 2017
	Breads and crackers	*Tetraselmis* sp., *Nannochloropsis* sp.	Lafarga *et al*., 2019
	Wheat crackers	*Arthrospira platensis, Chlorella vulgaris, Tetraselmis suecica, Phaeodactylum tricornutum*	Batista *et al*., 2019
	Cookies	*Haematococcus pluvialis*	Hossain *et al*., 2017
	Cookies and granola bars	*Chlorella vulgaris*	Gelgör *et al*., 2022

	Butter cookies		Gouveia *et al*., 2007
Pasta	Pasta	*Chlorella vulgaris, Chlorella vulgaris orange* (after *carotenogenesis*), *Arthrospira maxima*	Fradique *et al*., 2010
		Isochrysis galbana, Diacronema vlkianum	Fradique *et al*., 2013
		Dunaliella salina	El-Baz *et al*., 2017
		Fucus vesiculosus (seaweed)	Ribeiro *et al*., 2022
	Gluten-free pasta	*Laminaria ochroleuca* (seaweed) Fradinho *et al*., 2019	
	Gluten-free noodles	*Spirulina platensis*	Riyad *et al*., 2020
Emulsions	Oil/water emulsions	*Chlorella vulgaris* green, *Chlorella vulgaris* orange (after carotenogenesis)	Raymundo *et al*., 2005
		Chlorella vulgaris green, *Chlorella vulgaris* orange (after carotenogenesis), *Haematococcus pluvialis* (red, after carotenogenesis)	Gouveia *et al*., 2006
Gels	Vegetarian food	*Chlorella vulgaris, Haematococcus pluvialis, Arthrospira maxima, Diacronema vlkianum*	Batista *et al*., 2008
		Arthrospira maxima, Diacronema vlkianum	Gouveia *et al*., 2008a
		Haematococcus pluvialis, Arthrospira maxima	Batista *et al*., 2011; 2012
Drinks	Coffee Soda beverage	*Arthrospira platensis*	Matos *et al*., 2022

With the idea of having a nutritious food ready to be consumed, a snack added with 2.6% *Spirulina* sp. LEB-18 was designed; the product had a sensory acceptance of 82% and an increase of 22.6% in proteins, 28.1% in lipids and 46.4% in minerals with respect to the snack without *Spirulina*, in addition its physical properties were not affected. (Lucas *et al*., 2018). A corn flour-based snack was enriched with *Spirulina palatensis* powder, the contents of anthocyanins, vitamins, proteins, minerals, amino acids and essential fatty acids increased with a decrease in caloric availability. Excellent acceptance was achieved by panelists (Bayat-Tork *et al*., 2022). Bread is one of the most consumed food products in the world, which is why attempts have been made to nutritionally enrich it in various ways. In this sense, a study reported that in the bread making, red alga (*Kappaphycus alvarezii*) powder (2-8 %) was added to the wheat flour, seeking to improve the rheological properties of the dough and the quality of the bread. The water absorption of the dough was increased and the stickiness properties were decreased, achieving a firmer bread (Mamat *et al*., 2014). In another study, the biomass of algae *Cladophora* sp. and *Ulva* sp. in amounts of 2.5, 5.0 and 7.5% were added to the bread dough. The addition of macroalgae biomass increased the protein (16 to 18%) and fiber (1 to 2%) contents, while the lipids decreased (17 to 12%). Sensory and technological properties changed slightly compared to bread without seaweed (Menezes *et al*., 2015). The cultivation conditions of *Scenedesmus obliquus* (freshwater green microalgae) were established in order to increase its lipid, carbohydrate and protein content and thus use this alga in lyophilized form as a fortifying ingredient in the elaboration of a crunchy chocolate bar seeking to have a product with greater nutritional value due to its contribution of essential amino acids and fatty acids as well as other compounds with biological activity (Hlaing *et al*., 2020).

Spirulina sp. LEB-18 spray-dried and microencapsulated with maltodextrin and soy lecithin was added to milk that had chocolate powder, a chocolate-flavored milk beverage was obtained with an increase in protein and phenolic content and a reduction in total lipids. The drink presented good suspension stability and low hygroscopicity as well as adequate acceptance by the tasters (Batista de

Oliveira *et al*., 2021). *Spirulina* platensis was used to fortify a yogurt, the addition of 0.25% *Spirulina* accelerated the end of fermentation without affecting the sensory acceptability or textural properties of the final dairy product. The water retention capacity was improved with less whey syneresis during 28 days of storage, the coloring of the product was stable and the antioxidant activity of the yogurt was considerably improved (Barkallah *et al*., 2017). In fermented milk with a mixed culture (*Streptococcus thermophilus*, *Lactobacillus acidophilus* and *Bifidobacterium animalis* ssp. *lactis*) an aqueous extract of *Gracilaria domingensis* alga was evaluated as a substitute for gelatin. In the product added with alga, there were no changes in the pH, titratable acidity and viability of the fermenting bacteria in comparison with the milks fermented with gelatin and without texture modifying agent. The firmness, consistency, cohesion and viscosity index were approximately 10% higher in the fermented milk added with seaweed (Tavares-Estevam *et al*., 2016).

A vegetable cream (spinach, zucchini, chickpeas, leeks, broccoli and Swiss chard) was added with 3.0 and 1.5% unicellular microalgae (either *Chlorella vulgaris*, *Arthrospira platensis*, *Nannochloropsis oceanica* or *Tetraselmis chui*) powder. The cream added with 1.5% *Chlorella vulgaris* was observed as the best formulation, however, the creams added with the four microalgae were considered products with "high protein content" according to current EU legislation (Boukid *et al*., 2021). The biomass of *Spirulina maxima* and *Chlorella vulgaris* was used to enrich fresh spaghetti. The amount of algae added (0.5-2.0%) improved the firmness of the pasta without loss of color (orange or green) after cooking, and the acceptance by the panelists was higher compared to the pasta without microalgae, concluding that the microalgae biomass can improve the nutritional and sensory quality of pasta, without affecting its cooking properties and texture (Fradique *et al*., 2010).

In another study, 5% of the flour mixture for pasta was replaced with powdered biomass of the *Chlorella sorokiniana* microalga, in order to provide coloration avoiding artificial colorants. The microalga was previously analyzed to determine its nutritional quality. The pasta added with the microalga showed an increase in protein and lipid content of 15.7 and 4.1 %, respectively; the contents of polyunsaturated fatty acids, chlorophyll and carotenoids also increased (Bazarnova *et al*., 2021). Sea lettuce (*Ulva lactuca*), nori (*Porphyra tenera*) and wakame (*Undaria pinnatifida*) algae were incorporated separately in the preparation of wheat pasta; it was observed that cooking times decreased as well as a lower hardness value with higher adhesiveness and resilience values, colors were also observed in the pastas provided by each alga used and an increase in protein and soluble fiber content was achieved (Ainsa *et al*., 2022).

In a study, the addition of powder from the *Ulva intestinalis* alga and a sulfated polysaccharide on the shelf life of fish surimi was evaluated. With the addition of the two ingredients, lower TBARS (thiobarbituric acid reactive substance assay) values were observed after 6 months, compared to surimi without alga, and the texture and acceptability of the product was better than that of the control product (Jannat-Alipour *et al*., 2019). Lipid oxidation and physicochemical properties were evaluated in sausages made with chicken meat added with the edible alga *Kappaphycus alvarezii*. The presence of the alga increased the hardness and chewiness, the water retention capacity, the redness and the pH value of the sausages, there was also a reduction in lipid oxidation and cooking losses (Pindi *et al*., 2017). The addition of extracts of three brown marine algae (*Fucus vesiculosus*, *Ascophyllum nodosum* and *Bifurcaria bifurcata*) was evaluated on the oxidative rancidity of refrigerated low-fat pork liver pates. Half of the pork fat was replaced by canola and sunflower oil (75:25, v/v) and to prevent oxidation of polyunsaturated fatty acids, algal extracts were added. The protein content was increased (2-3%), without changes in the other chemical and microbiological components of the pate. After 180 days of storage, the algae showed a similar degree of protection against oxidation compared to BHT (Butyl hydroxytoluene) (Agregán *et al*., 2018). In one study, the ability of extracts (ethanolic and acetone) of the Icelandic brown alga *Fucus vesiculosus* to inhibit the oxidation of lipids present in granola bars fortified with fish oil-in-water emulsion was investigated. Algal extracts (0.5 or 1 g extract/100 g emulsion) reduced lipid oxidation during 10 weeks of storage. The antioxidant improvement was possibly due to the fact that the algal extracts improved the incorporation of the emulsions in the bars and increased the total phenolic content (Karadağ *et al*., 2017).

The alga *Himanthalia elongata* (10-40 % w/w) was added to cooked beef patties. Patties with seaweed showed reduced cooking losses and were nearly 50% more tender as compared to patties without seaweed. Microbial count and lipid oxidation were decreased compared to patties without seaweed. The content of dietary fiber, the content of phenolic compounds and the DPPH (2,2-Diphenyl-1-Picrylhydrazyl) radical scavenging activity increased considerably. The sensory analysis showed greater acceptance of the patties added with seaweed (Cox and Abu?Ghannam, 2013). In another study, the effect of incorporating the alga *Sargassum wightii* (0.3, and 5%) on the quality of tuna jerky was studied. The total fiber content increased up to 2.49% due to the addition of seaweed, the amounts of macrominerals and trace elements in the Tuna jerky also increased and the antioxidant activity was improved (Hanjabam *et al*., 2017).

Conclusions

Given the continuous growth of the human population, the demand for nutritious and healthy foods also grows, in this sense, functional foods or nutraceuticals are the object of search and study. Currently, algae have become very important due to their use as food or ingredient in the food industry due to its nutritional quality and the biological activities they present. It is extremely important to promote the consumption of algae in any of its presentations, in addition, research on the study of nutritional quality and nutraceutical properties and the design of new foods supplemented with algae should be increased.

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