TYPE Mini Review
PUBLISHED 16 September 2022
DOI 10.3389/frfst.2022.989801

Use of algae as food ingredient: sensory acceptance and commercial products

Ângelo Paggi Matos[1]*, Enrico Novelli[2] and Giustino Tribuzi[1]*

[1]Department of Food Science and Technology, Federal University of Santa Catarina, Florianópolis, SC, Brazil, [2]Department of Comparative Biomedicine and Food Science, University of Padua, Padua, Italy

Algal biomass or algae extracts can be used as food ingredients, meeting the needs of the consumers for nutritious, sustainable, and healthy food. Microalgae and macroalgae (seaweed) are rich in proteins, soluble fibers and polysaccharides, lipids and polyunsaturated fatty acids, pigments, vitamins, and minerals. However, one of the main challenges of using algae in food systems is related to the palatability of algae in terms of sensory as biomass may contain several odor-active volatile chemical compounds, which can be undesirable for certain algal-food product. This mini-review aim to provide an overview of nutritional compounds extracted from algae, while briefly discussing the main flavor compounds that directly affect the sensorial properties of algal biomass. Examples of new and sophisticated foods enriched with algal biomass such as plant-based fish, meat, and dairy analogues and innovative ingredients are also presented, elevating algae's credibility as a potential source for novel food development.

KEYWORDS

algal biomass, nutritional compounds, flavor, commercial algae-ingredient, volatiles compounds

Introduction to algae as food source

The increasing worldwide population is projected to be around 9.7 billion in 2050 (Ehrlich and Harte, 2015; UN DESA, 2022), with massive demand for proteins either from animal-based foods (meat, poultry, fish, eggs, and dairy foods) or plant-based foods (fruits, vegetable, grains, nuts, and seeds) has driven researchers to investigate more sustainable food sources such as algal-based foods (Matos, 2020; Amorim et al., 2021). Current protein demand is approximately 202 million tonnes globally (Henchion et al., 2017), and according to the British nutrition foundation, the reference nutrient intake (RNI) for protein for adults is 0.75 g protein per kg body weight per day; this equates to 56 g/day and 45 g/day for men and women of average body weights (75 and 60 Kg), respectively.

Algae represent an interesting possibility to supply the growing need for protein demand as well as a source of bioactive compounds such as amino acids, polyunsaturated fatty acids, vitamins, and minerals for the enrichment of traditional algal foods (Matos, 2017). Like tofu, tempeh, lentils, chickpeas, and almonds, algae and its byproducts can efficiently be used for the development of new foods, providing rich biomass as substitutes

Check for updates

OPEN ACCESS

EDITED BY
Rafik Balti,
University of Jendouba, Tunisia

REVIEWED BY
Paulo Eduardo Sichetti Munekata,
Centro Tecnologico de la Carne, Spain
Arivalagan Pugazhendhi,
Daegu University, South Korea

*CORRESPONDENCE
Ângelo Paggi Matos,
matos.a@posgrad.ufsc.br
Giustino Tribuzi,
giustino.tribuzi@ufsc.br

SPECIALTY SECTION
This article was submitted to Food Biotechnology,
a section of the journal
Frontiers in Food Science and Technology

RECEIVED 08 July 2022
ACCEPTED 24 August 2022
PUBLISHED 16 September 2022

CITATION
Matos ÂP, Novelli E and Tribuzi G (2022), Use of algae as food ingredient: sensory acceptance and commercial products. *Front. Food. Sci. Technol.* 2:989801.
doi: 10.3389/frfst.2022.989801

for plant-based meat alternatives (Onwezen et al., 2021). When following a plant-based diet, there are some key nutrients and/or products that consumers should focus on, such as plant-based foods rich in protein, vitamins, and minerals (vitamin B_{12}, vitamin D, and calcium) as well as essential omega-3 fatty acids (De Farias Neves et al., 2019). Additionally, polysaccharides like carrageen, alginate, and agar-agar extracted from seaweed are all widely used as additives or adjuvants for the food industry as thickening agents for drinks, ice cream, cosmetics, and as gelling agents for jellies (Hung et al., 2021). Sodium alginate, for instance, can be mixed with soybean flour to make meat or fish analogue (Zhang et al., 2020).

Several recent studies found in the literature have proposed the use of whole algae or algae extract for the development of new foods, with investigations on the digestibility and bioaccessibility of algal biomass in different food matrixes. For example, *1*) the sensory, physical, and chemical properties, antioxidant activity, and *in vitro* digestibility of microalgae biomass as an alternative ingredient in cookies was evaluated (Batista et al., 2017); 2) the nutritional, physical and sensory evaluations of *Arthrospira platensis* biomass for snack enrichment was investigated (Lucas et al., 2018); 3) the effect of *Spirulina* biomass on the technological and nutritional quality of bread wheat pasta was also investigated (Rodríguez Demarco et al., 2022); 4) the physical and antioxidant properties of gluten-free bread enriched with brown algae (*Ascophyllum nodosum*) was explored by Różyło et al. (2017); and 5) the biosorption of protein, minerals (Na, P, Ca, and Mg) and phenolic compounds of snack (extruded maize) enriched with *Porphyra columbina* was investigated by Cian et al. (2014). All these studies have shown the promising impact of consuming algae-based foods under *in vitro* experimental studies linked with the bioaccessibility of nutrients.

Other studies have reported that the addition of high concentration of algal biomass might result in negative effects on color and flavor of the final product, which depends on algae species and end product, decreasing consumers' acceptance (Geada et al., 2021). For this reason, a concentration of a maximum 5% (w/w) of algal biomass has been generally utilized and incorporated in algal-food products (Batista et al., 2017).

Considering the skyrocketing growth of the healthy and plant-based food sector, it is not surprising that algae are being pursued as a functional ingredient. Previously widely used in animal feed, the high protein yield of certain microalgae lends them to be an attractive ingredient for a variety of foodstuffs (Matos, 2019).

In this mini-review, the technological and practical aspects of using algae as an ingredient for food development are briefly discussed, showing challenges related to sensory properties and product acceptance as food ingredients, by consumers. Examples of novel food products are also presented, giving an overview of companies and their foods enriched with microalgae and/or seaweed biomass.

Algae are a suitable source of nutritional compounds?

The term "algae" is a collective term for various water-dwelling eukaryotes that perform photosynthesis. The size of the algae is a suitable differentiating feature with microalgae, often unicellular organisms, only viewed under a microscope (<100 µm), while macroalgae can be seen with the naked eye (Moheimani et al., 2015). In Asian culture, food products containing seaweed have been used directly in traditional foods, such as established nori (*e.g.*, *Porphyra*) for sushi or *Ulva lactuca* as sea lettuce (Fleurence, 2016). Further examples are wakame (*Undaria pinnatifida*), Kombu (*Saccharina japonica*), Irish moss (*Chondrus crispus*) and thongweed or sea spaghetti (*Himanthalia elongate*) (Parniakov et al., 2018), which provide texture and flavor to the food product (Taboada et al., 2013).

Microalgae are also increasingly used as ingredient for foods as a flavor active, texture enhancer or nutrients source (Coleman et al., 2022). Among the best-known microalgae species are *Arthrospira platensis* (*Spirulina*) and *Chlorella vulgaris*, which can act as a vegan protein source due to their high protein content (50%–60% of dry weight) with a complementary roll of essential amino acids and vitamin B_{12} (Figure 1) (Matos, 2019). These microalgae have been listed in the EU Novel food catalogue for food applications by the European Food Safety Authority (EFSA, https://webgate.ec.europa.eu/fip/novel_food_catalogue/) (Enzing et al., 2014) and approved by the United States Food Drug Administration (FDA) as generally recognized as safe (GRAS) (21CFR73.530 for Spirulina and GRN 000986 for Chlorella) (Harp and Barrows, 2015).

It is important to highlight that microalgae are considered an unconventional food source and have to undergo a series of toxicological tests to prove their harmlessness (Becker, 2007). For example, Becker (2013) has suggested that approval of algal biomass for human consumption should follow some quality and safety standards, such as 1) proximate chemical composition, 2) evaluation of protein quality and quantity of essential amino acids, 3) determination of biogenic toxic substances (phycotoxins and other toxicants), 4) identification of non-biogenic toxic compounds (heavy metals, residues from harvesting and processing), 5) sanitary analyses including contamination by microbial pathogens, and 6) toxicological and safety evaluations.

To be able to use algae skillfully for food nutrition, their contents of proteins, dietary fibers, omega-3 fatty acids,

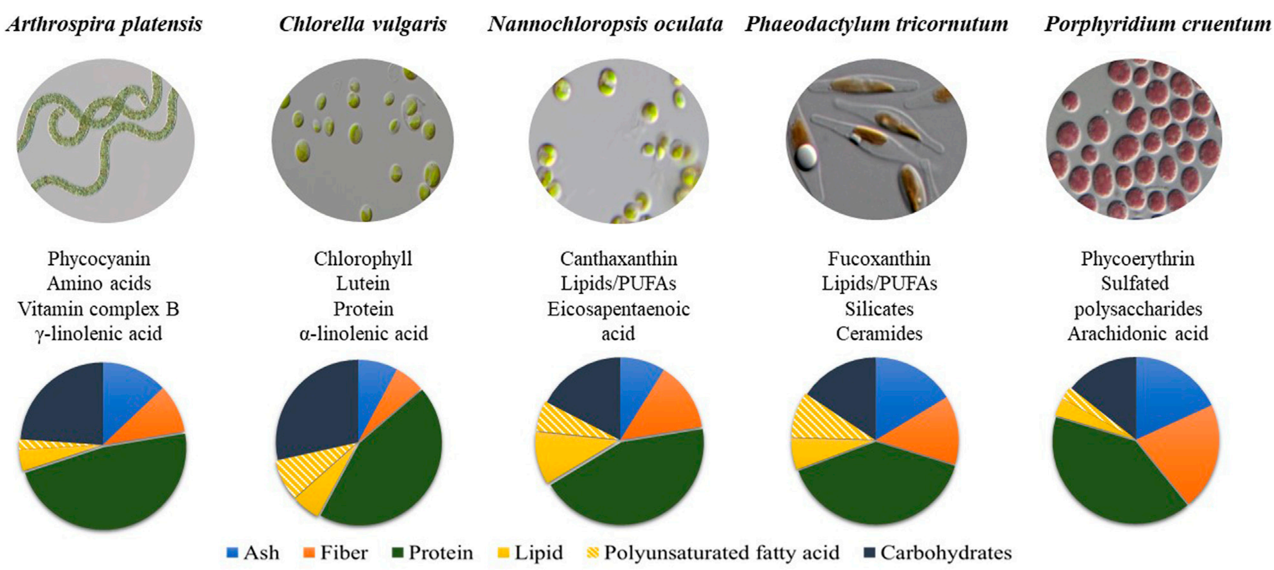

FIGURE 1
Examples of commercialized microalgae available in the market (free-access photos assembled from Culture Collection of Algae (SAG) at Goettingen University). Biochemical content of some microalgae species with emphasizes to the protein content highlighted in green color. Data obtained from Matos et al. (2016).

pigments, vitamins, and trace elements must be considered, in addition to their flavor, bioaccessibility, and processability. The main value-adding uses of algae in foods are listed below:

- Algae are suitable for fish and shellfish substitutes because of their specific flavor, which ranges from umami, salty, grassy, and nutty to extend neutral (Turchini et al., 2009).
- Algae can make a significant contribution to the supply of omega-3 fatty acids and thus take over the role of fish meat in the diet. Long-chain fatty acids like eicosapentaenoic acid (EPA, $C_{20:5\omega3}$) and docosahexaenoic acid (DHA, $C_{22:6\omega3}$) are generally ingested via fish oil and can be replaced by directly some microalgae (Matos, 2016).
- Algae are a primary source of natural pigments such as carotenes (β-carotene, lycopene and astaxanthin) and xanthophylls (lutein and zeaxanthin), which have several positive physiological effects on human health (Maoka, 2020).
- Vitamin B_{12}, known as cobalamin, which is primarily found in animal products, is also produced by certain algae, notably *Arthrospira platensis*. This alga is, therefore interesting to prevent a possible deficiency as a result of a vegan diet (Grosshagauer et al., 2020).
- In terms of trace elements like minerals, algae contain zinc, iron, selenium, potassium, and calcium, which are all essential microelements for human consumption and metabolism (Demarco et al., 2022).

Challenges Surrounding algal usage and food acceptance

One of the main important aspects of using algae in food systems are related to the palatability of algal biomass in terms of sensory input induced by aroma, color, taste (salty, sweet, sour, bitter, and umami) and textural mouthfeel (Isleten Hosoglu, 2018). The main characteristics of aroma in algae biomass is derived from a complex mixture of different odor-active volatile chemical compounds as stated by Coleman et al. (2022). In particular, four classes of typical odor-active volatile chemicals in algae are known: 1) fatty acid-derived volatiles compounds (aldehydes, alcohols and ketones) originated from the lypoxygenase activity or autoxidation of polyunsaturated fatty acids; 2) sulfuric compounds such as dimethyl sulfuric (DMS, $C_2H_6O_4S$), dimethyl disulfide (DMDS, $C_2H_6S_2$) and methanethiol (CH_4S); 3) nitrogen-containing compounds such as trimethylamine (TMA, C_3H_9N) originated from the action of microbial activity that reduces osmolyte trimethylamine oxide (TMAO) into TMA; and 4) umami taste compounds related to the presence of specific free amino acids such as glutamate (Glu) and aspartate (Asp) as well as nucleotides, notably inosine monophosphate (IMP), guanosine monophosphate (GMP) and adenosine monophosphate (AMP).

Extraction of free amino acids and 5′-nucleotides from seven Dutch seaweed species analyzed by reversed-phase and mixed-mode HPLC as key contributors to the acceptance of umami taste seaweed has been investigated (Moerdijk-Poortvliet et al., 2022). Authors have identified that *Phaeophyceae* seaweed class showed the highest equivalent umami concentration (EUC), followed by *Chlorophyceae* and *Rhodophyceae* (≈9.5, 3.7, and 1.1 g/100 g respectively). In addition, glutamic acid always exceeded the taste activity values (TAV), while other umami compounds were species-specific, indicating that the correct determination of EUC values in algae can tailoring the appropriate seaweed species towards a product readily accepted as food source (Mouritsen et al., 2019). In contrast to seaweeds, there is little knowledge about the contribution of flavor in microalgae biomass, despite the ample attention received by these microorganisms in the past decade as a novel source of food. For this reason, the aroma and taste of eight different phototrophic microalage species were investigated and compared with five seaweeds to evaluate their potential as flavor ingredients in plant-based seafood alternatives (Coleman et al., 2022). According to the results, microalgae *Rhodomonas salina*, *Tetraselmis chui*, and *Phaeodactylum tricornutum* have a stronger seafood odor and taste features compared to seaweeds. The microalage species *R. salina* and *T. chui* have higher crab flavoring aroma, while *P. tricornutum* possesses the highest bitterness taste, which could be unwanted in plant-based products. *T. chui* also presents a slightly grassy odor, while *Dunaliella salina* is characterized by floral notes due to the presence of carotenoids-derived compounds (*e.g.,* β-ionones).

Another notable study about aroma in microalgae was investigated by Isleten Hosoglu (2018), where the aroma characterization of five microalgae species (*Crypthecodinium cohnii*, *Schizochytrium limacinum*, *Tetraselmis chuii*, *Chlorella vulgaris* and *Chlorella protothecoides*) using solid-phase micro-extraction and gas chromatography-mass spectrometry/olfactometry was explored. The author remarkably stated that *C. cohnii* has a high level of sulfur compounds (dimethyl sulfide, ethanethiol), and ester and alcohol compounds associated with distinct 'sulfur-cabbage, fruity, rosy, boiled potato' aroma tastes. *S. limacinum* was characterized more by aldehydes and alcohol compounds linked with 'mushroom, cucumber and fatty-grassy' aroma attributes, while the other microalgae species showed moderate levels of ketone and terpene compounds with "woody and cereal-like" sensory qualities.

It is important to highlight that high protein content (28%–71% dry weight) of certain microalgae (Becker, 2007) could result in a high amount of free amino acids notably glutamic acid and aspartate, causing high umami taste desirable for the imparting flavor in plant-based seafood alternative (Coleman et al., 2022), whereas fishy off-flavors of microalgal biomass may be unwanted for certain food products (dairy foods, cookies, pasta, beverages, among others). In this way, advanced studies and investigations on the phytochemical compounds in microalgae are important to reveal the presence of volatile organic compounds that directly affect the sensorial properties of algal-based food products as well as its acceptance (Francezon et al., 2021).

Some authors have focused their research on evaluating the acceptance of algae as a food ingredient by consumers (Onwezen et al., 2021). For example, the motivational drivers and barriers of the adoption intention of *Spirulina*-enhanced food has been investigated (Moons et al., 2018), where health consciousness and the willingness to compromise on algal food taste are major motivational drivers of the adoption intention for sporting individuals, vegetarians, and foodies. Weinrich and Elshiewy (2019), for instance, have conducted a survey with 940 consumers from three different European countries (Germany: 315, Netherlands: 310, France: 315) to evaluate the preference and willingness to pay for meat substitutes based on microalgae biomass. Authors identified that consumers that see no need for meat in their diet have a higher probability to choose meat substitutes based on microalgae, while consumers with a strong habit for meat consumption show a negative relationship to choosing the meat substitutes based on microalgae. In general, consumers prefer products in which novel ingredients made from algae can be disguised due to their bitter taste and grassy odor (Onwezen et al., 2021). Disguising ingredients may increases familiarity with algae biomass due to its potential ability to mimic certain food ingredients such as seafood (Francezon et al., 2021). For example, the microalgae *R. salina* has the potential ability to act as flavoring agent in plant-based seafood because of its crab aroma, while *Tetraselmis chui* and *Phaeodactylum tricornutum* have strong seafood odor and a taste characterized by high umami and crab/shellfish flavor, which can be used to disguise flavor of animal-based seafood products (Coleman et al., 2022).

New food products derived from algal biomass

To track the newest news of food products enriched with algal biomass, the website Algae Planet accessed on https://algaeplanet.com/is a good reference that exhibits up-to-date information regarding algae industry. In Table 1, it is possible to visualize some examples of new food products under development based on either microalgae biomass or macroalgae also called kelp and/or seaweed.

There is a great concern that current microalgae-based foods on the market often have a 'grassy' taste, intense green color and fishy odor that many consumers consider unpleasant. To use microalgae as a flavor ingredient, it is important that aroma and taste compounds are present in adequate concentrations. To minimize the off-flavors in algal food products, the appropriate selection of algal strain (Coleman et al., 2022), screening and optimization of culture conditions (Latsos et al., 2021), phytochemical studies and characterization of odorant compounds (López-Pérez et al., 2017) are some key steps towards the successful development of algal-food product.

A good example of algal food (ingredients) that tastes better is the honey yellow *Chlorella* powder produced by a Portuguese company (https://www.allmicroalgae.com/en/). The company also

TABLE 1 New plant-based foods based on algal ingredients containing either microalgae or macroalgae (seaweed/kelp).

Type of food	Type of algae	Producer	Country	Highlights
Honey	*Chlorella* yellow powder	Allmicroalgae Natural Products	Portugal	Autotrophic organic *Chlorella vulgaris* with different characteristics (smooth-, honey- and white-*Chlorella*) based on carotenoid pigment (lutein/zeaxanthin)
Cheese	Microalgae	Sophie's BioNutrients/ Ingredion Idea Labs®	United States Singapore	Algal-based cheese substitute mimics natural Cheddar cheese. Vegan-friendly cheese
Soda beverage	*Arthrospira platensis*	Ful Soda	Netherlands	A sparkling *Spirulina* drink that gives nutritional punch as well as its distinctive blue color
Coffee	*Arthrospira platensis*	AAA Acelerator Group Europe AG	Switzerland	Coffee beans called 'Infinity blue' coated with a soluble protein extracted from *Spirulina*
			Spain	
Powder of algal proteins	*Chlamydomonas*	Kuehnle AgroSystems (KAS)	Honolulu, Hawaii	Development of algal proteins and ingredients from *Chlamydomonas* dark fermentation
Unami™	Microalgae oil	Ocean Hugger Foods	United States	Substitute for conventional freshwater eel (unagi) made with eggplant, soy source, mirin, sugar, rice bran oil, algae oil and konjac powder
Substitute for tuna	Algae biomass	Hooked	United States	Substitute for tuna fish made with soybeans, sunflower oil and algae
Smoked vegetable solmontranches	Seaweed and microalgae	Odontella	France	The product is a substitute for conventional salmon based on a macerate of microalgae and seaweed (10%) with complimentary additives
Alternative bacon	Red seaweed	Umaro Foods	United States	The company makes plant-based meat alternatives using red seaweed with a superior taste, texture and nutritional profile
Cranberry kelp cubes	Seaweed	Atlantic sea farms	United States	The cranberry kelp cubes offer a way to combine two superfoods that come from regenerative farming practices
Dense hydrocolloid	Red seaweed	International Flavors & Fragances Inc	United States	A nutrient-dense hydrocolloid sourced from non-GMO red seaweed

Source: https://algaeplanet.com/.

produces autotrophic organic *Chlorella vulgaris* with different characteristics (smooth-, honey- and white-*Chlorella*). The new *Chlorella* strain has a higher protein content (35%–40% per dry weight), and most importantly, from a consumer perspective, does not give food products the off-putting fishiness. To arrive at the new *Chlorella* strain, the researchers have applied random mutagenesis tool that induces mutations, generating proteins, enzymes and even entire genomes with improved properties. The new *Chlorella* strain developed by this company is then fully characterized from biochemical, technological, and sensorial perspectives to develop alternative food products such as cookies and biscuits (Gouveia et al., 2007; Batista et al., 2017), bread and pasta with improved nutritional value and organoleptic properties (Fradique et al., 2010; Diprat et al., 2020).

Kuehnle AgroSystems (KAS) (https://www.kuehnleagro.com/), a sustainable algae ingredients development company based in Honolulu, Hawaii, has announced the allowance of its patent for producing microalgal proteins and other products by culturing *Chlamydomonas* microalgae via dark fermentation (https://patentscope.wipo.int/search/en/detail.jsf?docId = WO2018006068). Unlike some microalgae, including *Chlorella*, the *Chlamydomonas* group of microalgae is distinguished by their soft and non-cellulosic cell wall that do not require added processing such as cell disruption to render its nutrients bioavailable (Fields et al., 2020). The company notes that the patented process covers the production of additional ingredients for adding color, flavor, and vital nutrients that can be used for plant-based meat and seafood, such as hematoproteins and selenoproteins, produced by members of the Chlamydomonadales (Kaur et al., 2009). Colors of the *Chlamydomonas reinhardtii* biomass produced by the dark fermentation process range from green and yellow to achlorophyllic color (in part from lutein/zeaxanthin), which is derived from a *C. reinhardtii* population of previously cryopreserved cells revived under mixotrophic conditions. The microalgal example also pertains to cell types of UV light-induced and chemically induced *Chlamydomonas* mutants (strain KAS 1602—variant derived from CC-125 or 137c) that lack carotenoids, providing different colors than the typical green (further descriptions about this patented process can be found in WO2018006068). The *Chlamydomonas* contains more than 60% of protein while delivering minerals, vitamins, antioxidants, and other components valued for foods, beverages, and nutraceuticals (Darwish et al., 2020).

Another distinguished foodstuff from microalgae is the microalgae-based cheese substitute, made from Sophie's BioNutrients® dairy-free microalgae milk (https://algaeplanet.com/sophies-closes-in-on-the-algal-bacon-cheeseburger/).

Sophie's BioNutrients, a next-generation sustainable urban food technology company, together with Ingredion Idea Labs® innovation center in Singapore, have collaborated to elaborate an algal-based cheese substitute that mimics natural Cheddar cheese. This product is developed using microalgae protein flour, and it is available as two types of products—a semi-hard microalgae dairy-free product and a dairy-free spread. Mohamed et al. (2013), for instance, have tested the quality in terms of chemical composition, physical properties and sensory acceptance of novel healthy processed cheese analogue enhanced with marine microalgae *Chlorella vulgaris* biomass. Cheese analogue is processed as a cheese-like product where milk fat, milk protein or both are partially or wholly replaced by non-milk-based components (Fox et al., 2017).

The bioproducts derived from *Arthrospira platensis* microalgae, notably protein and phycocyanin-pigment, have been used for many industrial applications (Lafarga et al., 2021), including for example the development soda beverage with blue-phycocyanin pigment (Jespersen et al., 2005), where authors studied the stabilities of three natural blue colorants (gardenia blue, phycocyanin and indigo) for use in confectionary and beverages under investigation of various pH toward heat and light exposition. Authors stated that phycocyanin was found to be insoluble in acidic solution (pH 3.0) and denatures at temperatures above 45°C at pH 5.0 and 7.0, causing degradation of −80% of the pigment as well as color change. Moreover, exploratory studies with the three blue colorants in model foods and beverages such as soft drinks, jelly gum, and sugar coating for soft candy showed that phycocyanin was a more versatile blue food colorant due to its inherent bright blue color in jelly gum and coated soft candy (De Amarante et al., 2020; Luzardo-Ocampo et al., 2021).

A new sophisticated coffee bean product called "Infinity Blue" was recently developed by The AAA Accelerator Group Europe AG, in Switzerland, and its biotech subsidiary Algatek Asturias, S.L., of Teverga Asturias Spain. The coffee bean production process for Infinity Blue has been registered for patent for coating the coffee beans with a soluble protein extracted from *Arthrospira platensis* biomass yielding a blue coffee bean that gives the consumer proteins not present in other coffee drinks. The coating also protects the coffee bean flavor, keeping the beans fresh for longer and locking in a premium coffee taste (https://algaeplanet.com/aaa-accelerator-and-algatek-introduce-infinity-blue-coffee/). Thinking in this soluble protein from *A. platensis*, Ramírez-Rodrigues et al. (2021) have investigated the techno-functional properties of a protein isolate from *A. platensis* biomass. Protein isolate was characterized in terms of protein content, structure (molecular mass, secondary structure, and thermal behavior) and functionality (emulsion capacity and stability) and was tested in two food prototypes, *i.e.*, mayonnaise and fettuccine pasta. *A. platensis* protein isolate with sodium alginate (0.5%) produced stable emulsions (˃90%) during 14 days of storage and is comparable to the most commercially used protein in food products as a techno-functional additive.

Taking into account the potential of macroalgae as a potential source of protein, a Berkeley, California-based Umaro Foods (https://www.umarofoods.com/) has been showcasing an interesting and innovative plant-based bacon product. The company's bacon benefits from two proprietary innovations. The first is the company's own protein, UMARO™, which it extracts from ocean-farmed red seaweeds and that serves as a technological replacement for 'heme' group, the red protein molecule that makes plant-based meat "bleed" and provides the typical meat color. The second is the use of seaweed-based ingredients to encapsulate plant-based oils into a fat crisps and crunches just like animal fat. Meat and meat products have a central role in many food cultures, and transition towards to plant-based meat alternatives (PBMAs) have been identified as a key measure to promote health, while minimizing the impact of animal farming on the environment (Tso and Forde, 2021). Thus, an excellent review of research on plant-based meat analogue, including seaweed-based bacon, was discussed in detail in He et al. (2020), where driving forces for PBMA development, history of its progression, key technologies required for production, consumer attitudes and future research opportunities were summarized by the authors.

Another notable example of by-product made from red seaweed is the SEAFLOUR™ produced by International Flavors & Frangances company (https://www.iff.com/sustainableseaweed). SEAFLOUR, also known as 'seaweed flour' is an ingredient with the properties to be a natural stabilizer that contains protein, fiber and minerals, offering food product stability, a high-suspension ability and excellent mouthfeel. This newly algal product is destined for plant-based beverage applications such as nut- and soy-based milk. The effect of seaweed flour incorporated in different foods has been previously tested such as 1) the effect of seaweed composite flour on the textural properties of dough and bread (Mamat et al., 2014); 2) the influence of seaweed composite flour on the physicochemical properties of muffin (Mamat et al., 2018); 3) the fermentation of seaweed flour with various fermenters to improve the quality of fish feed ingredients (Aslamyah et al, 2017), and 4) the fortification of seaweed flour on nutrition, iodine and glycemic index of pasta (Firdaus et al., 2017). All these studies have been shown the positive effect of adding seaweed flour in foodstuff as well as the significance of seaweed-based food for human health promotion (Lucas et al., 2019).

Conclusion

The search for novel foods and ingredients using algae either microalgae or seaweed biomass with remarkable nutritional, sensorial, and technological properties originated by sustainable food systems has grown exponentially in recent years. Few studies have investigated the chemical flavor compounds that impact the sensorial appeal of algal biomass, while other studies have focused their research on identifying the motivational drivers and barriers by the consumers in adopting a diet with algal biomass, where health consciousness and the willingness to compromise the algal-food taste are major concerns. New sophisticated microalgal-food products have been developed such as honey *Chlorella* yellow powder, sparkling water with distinct blue color from phycocyanin pigment, and coffee beans coated with soluble protein extracted from *Arthrospira*, while algal Cheddar cheese substitute, red seaweed as a substitute for bacon and conventional salmon are some novel algal-based food products, providing rich and nutritious biomass for human consumption. Future research on the influence of culture conditions that directly affect the synthesis of volatile compounds, free amino acids, and free nucleotides produced by different types of algae are necessary to bring closer readiness algal-based products with good sensory appeal for consumption.

Author contributions

APM: bibliographic investigations, writing—original draft, and writing—review and editing. GT: conceptualization, writing—original draft and writing—review and editing, supervising. EN: writing—review and editing, supervision. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Amorim, M. L., Soares, J., Coimbra, J. S. D. R., Leite, M. D. O., Albino, L. F. T., and Martins, M. A. (2021). Microalgae proteins: Production, separation, isolation, quantification, and application in food and feed. *Crit. Rev. Food Sci. Nutr.* 61, 1976–2002. doi:10.1080/10408398.2020.1768046

Aslamyah, S., Karim, M. Y., and Badraeni, B (2017). Fermentation of seaweed flour with various fermenters to improve the quality of fish feed ingredients. *J. Akuakultur Indones.* 16, 8–14. doi:10.19027/jai.16.1.8-14

Batista, A. P., Niccolai, A., Fradinho, P., Fragoso, S., Bursic, I., Rodolfi, L., et al. (2017). Microalgae biomass as an alternative ingredient in cookies: Sensory, physical and chemical properties, antioxidant activity and *in vitro* digestibility. *Algal Res.* 26, 161–171. doi:10.1016/j.algal.2017.07.017

Becker, E. W. (2007). Micro-algae as a source of protein. *Biotechnol. Adv.* 25, 207–210. doi:10.1016/j.biotechadv.2006.11.002

Becker, E. W. (2013). Microalgae for human and animal nutrition. *Handb. Microalgal Cult. Appl. Phycol. Biotechnol.* 2013, 461–503. doi:10.1002/9781118567166.ch25

Cian, R. E., Fajardo, M. A., Alaiz, M., Vioque, J., González, R. J., and Drago, S. R. (2014). Chemical composition, nutritional and antioxidant properties of the red edible seaweed *Porphyra columbina*. *Int. J. Food Sci. Nutr.* 65, 299–305. doi:10.3109/09637486.2013.854746

Coleman, B., Van Poucke, C., Dewitte, B., Ruttens, A., Moerdijk-Poortvliet, T., Latsos, C., et al. (2022). Potential of microalgae as flavoring agents for plant-based seafood alternatives. *Future Foods* 5, 100139. doi:10.1016/j.fufo.2022.100139

Darwish, R., Gedi, M. A., Akepach, P., Assaye, H., Zaky, A. S., and Gray, D. A. (2020). *Chlamydomonas reinhardtii* is a potential food supplement with the capacity to outperform *Chlorella* and *Spirulina*. *Appl. Sci.* 10, 6736. doi:10.3390/app10196736

De Amarante, M. C. A., Braga, A. R. C., Sala, L., and Kalil, S. J. (2020). Colour stability and antioxidant activity of C-phycocyanin-added ice creams after *in vitro* digestion. *Food Res. Int.* 137, 109602. doi:10.1016/j.foodres.2020.109602

De Farias Neves, F., Demarco, M., and Tribuzi, G. (2019). "Drying and quality of microalgal powders for human alimentation," in *Microalgae-from physiology to application* (London, UK: IntechOpen).

Demarco, M., Oliveira De Moraes, J., Matos, Â. P., Derner, R. B., De Farias Neves, F., and Tribuzi, G. (2022). Digestibility, bioaccessibility and bioactivity of compounds from algae. *Trends Food Sci. Technol.* 121, 114–128. doi:10.1016/j.tifs.2022.02.004

Diprat, A. B., Thys, R. C. S., Rodrigues, E., and Rech, R. (2020). *Chlorella sorokiniana*: A new alternative source of carotenoids and proteins for gluten-free bread. *Lwt* 134, 109974. doi:10.1016/j.lwt.2020.109974

Ehrlich, P. R., and Harte, J. (2015). Opinion: To feed the world in 2050 will require a global revolution. *Proc. Natl. Acad. Sci. U. S. A.* 112, 14743–14744. doi:10.1073/pnas.1519841112

Enzing, C., Ploeg, M., Barbosa, M., and Sijtsma, L. (2014). Microalgae-based products for the food and feed sector: An outlook for Europe. *JRC Sci. policy Rep.* 2014, 19–37. doi:10.2791/3339

Fields, F. J., Lejzerowicz, F., Schroeder, D., Ngoi, S. M., Tran, M., and McDonald, D. (2020). Effects of the microalgae Chlamydomonas on gastrointestinal health. *J. Funct. Foods* 65, 103738. doi:10.1016/j.jff.2019.103738

Firdaus, M., Nugraha, G. R. H., and Utari, D. D. (2017). "Fortification of seaweed (*Eucheuma cottonii*) flour on nutrition, iodine, and glycemic index of pasta," in IOP Conference Series: Earth and Environmental Science, Langgur City, Southeast Maluku, Indonesia, 22–25 August 2017, 012011.

Fleurence, J. (2016). *Seaweeds as food. Seaweed in health and disease prevention*. Amsterdam, Netherlands: Elsevier, 149–167.

Fox, P. F., Guinee, T. P., Cogan, T. M., and Mcsweeney, P. L. (2017). "Processed cheese and substitute/imitation cheese products," in *Fundamentals of cheese science* (Cham: Springer), 589–627.

Fradique, M., Batista, A. P., Nunes, M. C., Gouveia, L., Bandarra, N. M., and Raymundo, A. (2010). Incorporation of *Chlorella vulgaris* and *Spirulina maxima* biomass in pasta products. Part 1: Preparation and evaluation. *J. Sci. Food Agric.* 90, 1656–1664. doi:10.1002/jsfa.3999

Francezon, N., Tremblay, A., Mouget, J.-L., Pasetto, P., and Beaulieu, L. (2021). Algae as a source of natural flavors in innovative foods. *J. Agric. Food Chem.* 69, 11753–11772. doi:10.1021/acs.jafc.1c04409

Geada, P., Moreira, C., Silva, M., Nunes, R., Madureira, L., Rocha, C. M., et al. (2021). Algal proteins: Production strategies and nutritional and functional properties. *Bioresour. Technol.* 332, 125125. doi:10.1016/j.biortech.2021.125125

Gouveia, L., Batista, A. P., Miranda, A., Empis, J., and Raymundo, A. (2007). *Chlorella vulgaris* biomass used as colouring source in traditional butter cookies. *Innovative Food Sci. Emerg. Technol.* 8, 433–436. doi:10.1016/j.ifset.2007.03.026

Grosshagauer, S., Kraemer, K., and Somoza, V. (2020). The true value of *Spirulina*. *J. Agric. Food Chem.* 68, 4109–4115. doi:10.1021/acs.jafc.9b08251

Harp, B., and Barrows, J. (2015). "US regulation of color additives in foods," in *Colour additives for foods and beverages* (Amsterdam, Netherlands: Elsevier), 75–88.

He, J., Evans, N. M., Liu, H., and Shao, S. (2020). A review of research on plant-based meat alternatives: Driving forces, history, manufacturing, and consumer attitudes. *Compr. Rev. Food Sci. Food Saf.* 19, 2639–2656. doi:10.1111/1541-4337.12610

Henchion, M., Hayes, M., Mullen, A. M., Fenelon, M., and Tiwari, B. (2017). Future protein supply and demand: Strategies and factors influencing a sustainable equilibrium. *Foods* 6, 53. doi:10.3390/foods6070053

Hung, L. D., Nguyen, H. T. T., and Trang, V. T. D. (2021). Kappa carrageenan from the red alga *Kappaphycus striatus* cultivated at vanphong bay, vietnam: Physicochemical properties and structure. *J. Appl. Phycol.* 33, 1819–1824. doi:10.1007/s10811-021-02415-1

Isleten Hosoglu, M. (2018). Aroma characterization of five microalgae species using solid-phase microextraction and gas chromatography–mass spectrometry/olfactometry. *Food Chem.* 240, 1210–1218. doi:10.1016/j.foodchem.2017.08.052

Jespersen, L., Strømdahl, L. D., Olsen, K., and Skibsted, L. H. (2005). Heat and light stability of three natural blue colorants for use in confectionery and beverages. *Eur. Food Res. Technol.* 220, 261–266. doi:10.1007/s00217-004-1062-7

Kaur, G., Khattar, J. I. S., Singh, D. P, Singh, Y., and Nadda, J. (2009). "Microalgae: A source of natural colours," in *Algal Biol. Biotechnol*. Editors J. I. S. Khattar, D. P Singh, and G. Kaur (New Delhi: IK International Publishers), 129–149.

Lafarga, T., Sánchez-Zurano, A., Villaró, S., Morillas-España, A., and Acién, G. (2021). Industrial production of *Spirulina* as a protein source for bioactive peptide generation. *Trends Food Sci. Technol.* 116, 176–185. doi:10.1016/j.tifs.2021.07.018

Latsos, C., Bakratsas, G., Moerdijk, T., Van Houcke, J., and Timmermans, K. R. (2021). Effect of salinity and pH on growth, phycoerythrin, and non-volatile umami taste active compound concentration of *Rhodomonas salina* using a D-optimal design approach. *J. Appl. Phycol.* 33, 3591–3602. doi:10.1007/s10811-021-02547-4

López-Pérez, O., Picon, A., and Nuñez, M. (2017). Volatile compounds and odour characteristics of seven species of dehydrated edible seaweeds. *Food Res. Int.* 99, 1002–1010. doi:10.1016/j.foodres.2016.12.013

Lucas, B. F., Morais, M. G. D., Santos, T. D., and Costa, J. a. V. (2018). *Spirulina* for snack enrichment: Nutritional, physical and sensory evaluations. *LWT* 90, 270–276. doi:10.1016/j.lwt.2017.12.032

Lucas, S., Gouin, S., and Lesueur, M. (2019). Seaweed consumption and label preferences in France. *Mar. Resour. Econ.* 34, 143–162. doi:10.1086/704078

Luzardo-Ocampo, I., Ramírez-Jiménez, A. K., Yañez, J., Mojica, L., and Luna-Vital, D. A. (2021). Technological applications of natural colorants in food systems: A review. *Foods* 10, 634. doi:10.3390/foods10030634

Mamat, H., Akanda, J. M. H., Zainol, M. K., and Ling, Y. A. (2018). The influence of seaweed composite flour on the physicochemical properties of muffin. *J. Aquatic Food Prod. Technol.* 27, 635–642. doi:10.1080/10498850.2018.1468841

Mamat, H., Matanjun, P., Ibrahim, S., Abdul Hamid, M., and Rameli, A. S. (2014). The effect of seaweed composite flour on the textural properties of dough and bread. *J. Appl. Phycol.* 26, 1057–1062. doi:10.1007/s10811-013-0082-8

Maoka, T. (2020). Carotenoids as natural functional pigments. *J. Nat. Med.* 74, 1–16. doi:10.1007/s11418-019-01364-x

Matos, Â. P. (2016). Essential fatty acids from microalgae. *Inform* 27, 22–26. doi:10.21748/inform.11.2016.22

Matos, Â. P., Feller, R., Moecke, E. H. S., De Oliveira, J. V., Junior, A. F., Derner, R. B., et al. (2016). Chemical characterization of six microalgae with potential utility for food application. *J. Am. Oil Chem. Soc.* 93, 963–972. doi:10.1007/s11746-016-2849-y

Matos, Â. P. (2019). "Microalgae as a potential source of proteins," in *Proteins: Sustainable source, processing and applications* (Amsterdam, Netherlands: Elsevier), 63–96.

Matos, Â. P. (2020). *Review of the book "proteins: Sustainable source, processing, and applications"*. Amsterdam, Netherlands: Elsevier.

Matos, Â. P. (2017). The impact of microalgae in food science and technology. *J. Am. Oil Chem. Soc.* 94, 1333–1350. doi:10.1007/s11746-017-3050-7

Moerdijk-Poortvliet, T. C., De Jong, D. L., Fremouw, R., De Reu, S., De Winter, J. M., Timmermans, K., et al. (2022). Extraction and analysis of free amino acids and 5′-nucleotides, the key contributors to the umami taste of seaweed. *Food Chem.* 370, 131352. doi:10.1016/j.foodchem.2021.131352

Mohamed, A., Abo-El-Khair, B., and Shalaby, S. M. (2013). Quality of novel healthy processed cheese analogue enhanced with marine microalgae *Chlorella vulgaris* biomass. *World Appl. Sci. J.* 23, 914–925.

Moheimani, N. R., Mchenry, M. P., De Boer, K., and Bahri, P. A. (2015). "Biomass and biofuels from microalgae," in *Biofuel and biorefinery technologies* (Cham: Springer-Verlag GmbH).

Moons, I., Barbarossa, C., and De Pelsmacker, P. (2018). The determinants of the adoption intention of eco-friendly functional food in different market segments. *Ecol. Econ.* 151, 151–161. doi:10.1016/j.ecolecon.2018.05.012

Mouritsen, O. G., Duelund, L., Petersen, M. A., Hartmann, A. L., and Frøst, M. B. (2019). Umami taste, free amino acid composition, and volatile compounds of Brown seaweeds. *J. Appl. Phycol.* 31, 1213–1232. doi:10.1007/s10811-018-1632-x

Onwezen, M. C., Bouwman, E. P., Reinders, M. J., and Dagevos, H. (2021). A systematic review on consumer acceptance of alternative proteins: Pulses, algae, insects, plant-based meat alternatives, and cultured meat. *Appetite* 159, 105058. doi:10.1016/j.appet.2020.105058

Parniakov, O., Toepfl, S., Barba, F. J., Granato, D., Zamuz, S., Galvez, F., et al. (2018). Impact of the soy protein replacement by legumes and algae based proteins on the quality of chicken rotti. *J. Food Sci. Technol.* 55, 2552–2559. doi:10.1007/s13197-018-3175-1

Ramírez-Rodrigues, M. M., Estrada-Beristain, C., Metri-Ojeda, J., Pérez-Alva, A., and Baigts-Allende, D. K. (2021). *Spirulina platensis* protein as sustainable ingredient for nutritional food products development. *Sustainability* 13, 6849. doi:10.3390/su13126849

Rodríguez De Marco, E., Steffolani, M. E., Martínez, C. S., and León, A. E. (2014). Effects of *Spirulina* biomass on the technological and nutritional quality of bread wheat pasta. *LWT - Food Sci. Technol.* 58, 102–108. doi:10.1016/j.lwt.2014.02.054

Różyło, R., Hameed Hassoon, W., Gawlik-Dziki, U., Siastała, M., and Dziki, D. (2017). Study on the physical and antioxidant properties of gluten-free bread with Brown algae. *CyTA - J. Food* 15, 196–203. doi:10.1080/19476337.2016.1236839

Taboada, M. C., Millán, R., and Miguez, M. I. (2013). Nutritional value of the marine algae wakame (*Undaria pinnatifida*) and nori (*Porphyra purpurea*) as food supplements. *J. Appl. Phycol.* 25, 1271–1276. doi:10.1007/s10811-012-9951-9

Tso, R., and Forde, C. G. (2021). Unintended consequences: Nutritional impact and potential pitfalls of switching from animal-to plant-based foods. *Nutrients* 13, 2527. doi:10.3390/nu13082527

Turchini, G. M., Torstensen, B. E., and Ng, W. K. (2009). Fish oil replacement in finfish nutrition. *Rev. Aquac.* 1, 10–57. doi:10.1111/j.1753-5131.2008.01001.x

UN DESA (2022). *World population prospects 2022: Summary of results*. New York: UNDESA.

Weinrich, R., and Elshiewy, O. (2019). Preference and willingness to pay for meat substitutes based on micro-algae. *Appetite* 142, 104353. doi:10.1016/j.appet.2019.104353

Zhang, J., Liu, L., Jiang, Y., Shah, F., Xu, Y., and Wang, Q. (2020). High-moisture extrusion of peanut protein-/carrageenan/sodium alginate/wheat starch mixtures: Effect of different exogenous polysaccharides on the process forming a fibrous structure. *Food Hydrocoll.* 99, 105311. doi:10.1016/j.foodhyd.2019.105311