Effect of microalgal biomass incorporation into foods: Nutritional and sensorial attributes of the end products

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Abbreviations:

DHA: docosahexaenoic acid; FDA: Food and Drug Administration of the United States of America; EU: European Union; EFSA: European Food Safety Authority; PUFAs: polyunsaturated fatty acids; EPA: eicosapentaenoic acid; DPA: docosapentaeonic acid.

Abstract

Despite the high content of macro- and micro-nutrients found in microalgae, only a limited number of products containing microalgae have been launched into the market. Most of these products were marketed as dietary supplements and sold as capsules, tablets, or a dried powder. However, nowadays, consumers demand for sophisticated and innovative products, and microalgal biomass and products derived thereof are positioning firmly in the food market. The current paper summarises the current situation of microalgae in the food industry, reviewing the most recent microalgae-containing products launched into the market worldwide. These can be divided into two major groups: (i) those foods that use microalgal biomass as a colouring agent and (ii) those that use this valuable resource as a marketing strategy or to improve the nutritional, physicochemical, and/or sensorial attributes of the end products. Moreover, the number of scientific publications evaluating the effect of microalgae-incorporation into the technofunctional, nutritional, and sensorial properties of foods is limited. Incorporation of microalgal biomass into foods found several challenges in the past, mainly because of their intense colour or their fishy taste and odour. However, several studies demonstrated that microalgae can be incorporated into food products with high physicochemical, nutritional, and sensorial quality. The amount of microalgae-containing foods launched into the market is increasing. Microalgae can be seen as a novel or trendy ingredient, but this valuable resource has potential to become a staple food for consumers all over the planet.

Keywords: Microalgae; novel ingredients; functional foods; proteins; pigments; product development

1. Introduction

Currently, consumers demand for sophisticated and innovative products, and microalgal biomass and products derived thereof are positioning firmly in the food market. Indeed, over the last decade, several companies prominent in the production and commercialisation of food have begun to involve themselves in developing foods containing microalgae or cyanobacteria [1]. This is a global trend. For example, in Europe it is possible to find *Follow Your Heart® VeganEgg* (Earth Island, USA), a vegan egg replacer produced from native microalgae originally found in the Netherlands, and in Asia it is possible to buy *Spirulina Filled Crackers* (Lee Biscuits, Malaysia). In the Americas, some of the most recent product launches containing microalgae include *Züpa Superfood Soup* (Züpa Noma, USA), an organic cucumber and avocado soup containing *Spirulina*, and *Chia & Spirulina Roo'Bar* (Roo Brands, Bulgaria), which is a protein bar rich in proteins commercialised in Canada.

Despite the huge range of opportunities that this resource offers and the known health benefits of microalgae consumption, which have been reviewed in several review papers and book chapters [2-8], most of the microalgae currently commercialised for food uses are sold as dietary supplements. Only a limited number of foods containing microalgae or microalgae-derived compounds have been recently launched into the market. Most of them are infant formula containing microalgae-derived docosahexaenoic acid (DHA) rather than products containing the whole microalgal biomass. There are still several challenges that need to be overcome, which include: (i) low production capacities; (ii) high production costs; (iii) an intense (generally green) colour and a fishy taste and aroma; and (iv) legislative and regulatory issues, among others. However, industrial production of microalgae-containing foods is a reality and several beverages, snacks, or baked goods containing microalgae are being commercialised worldwide. Several aspects need to be considered when developing a novel microalgae-containing product. For example, Chacón-Lee and González-Mariño [1] reviewed the potential food applications of microalgae and concluded that the degree of acceptability of microalgae-containing products depend largely on the traditional diet of the target population. Indeed, in many Asian countries, the use of microalgae as a food ingredient is not rare since traditional cuisine includes algae in many preparations. In Western cultures, several strategies, such as masking the intense colour of microalgae using chocolate, have been studied [9]. Chacón-Lee and González-Mariño [1] suggested that the strong flavour of microalgae could be masked by, for example, exotic-flavoured spices. However, the flavour of microalgae could be an opportunity to develop novel foods. For example, Fradique et al. [10] developed spaghettis containing microalgae and suggested that the fishy flavour and odour of the products could be an opportunity to prepare fish-based culinary preparations rather than a disadvantage. The Spanish company Fitoplancton Marino S.L. (Cadiz, Spain) is currently commercialising the product *Plancton Marino Veta la Palma*®, which is a freeze-dried *Tetraselmis chuii* product used to accentuate the marine flavour of foods. There is still a huge untapped opportunity for utilising microalgae as food. Indeed, astaxanthin, which is a carotenoid produced by the microalgae *Haematococcus pluvialis* has been recently suggested as one of the three main ingredients to watch during 2019 and a niche ingredient with strong potential [11]. The aim of this paper is to give a critical point of view on the culinary possibilities of microalgae, a currently underutilised ingredient that will be certainly finally exploited by the food industry. This paper will summarise some of the most recent products launched into the market, as well as the latest scientific findings on the effect of microalgae incorporation into foods.

2. Microalgae as food: Current situation

Food supplements are increasingly popular worldwide. The majority of the microalgal biomass currently commercialised is sold as a nutritional supplement in tablet, capsule, or powdered form and promoted as “superfoods”, “rich in proteins”, and/or “rich in omega-3”. Most often, such products contain the biomass of *Spirulina*. Examples of *Spirulina*-based supplements include *Dragon Superfoods Spirulina powder* (Smart Organic, Germany), *Apollo Hospitals Life Spirulina* (Apollo Pharmacy, India), and *Label Spiruline La Ferme de Bancel* (Label Spiruline, France), which are commercialised as the dried powder, as capsules, or as flakes, respectively. Other microalgal species such as *Haematococcus*, *Dunaliella*, and *Chlorella* are now being commercialised. Examples *Laboratoires Lierac Sunissime* (Laboratoires Liérac, France), which are “tanning capsules” rich in carotenoids made using an extract obtained from *Dunaliella salina*, and *Jeil Health Science Eyetreasure* (Jeil Health Science, South Korea), which contains lutein and astaxanthin obtained from *Haematococcus* and is claimed to help relieve eye strain and maintain the density of macular pigments, among other positive outcomes.

Nowadays, the trend is to incorporate microalgal biomass of compounds derived from microalgae as an ingredient in food formulations. The number of foods containing microalgae as an ingredient launched into the market has significantly increased during the past 4-5 years. Food products containing microalgae can be divided into two main groups: those that contain the whole microalgal biomass and those that contain a microalgae-derived compound. The latter includes food containing DHA- and EPA-rich oil extracted from the microalgae *Schizochytrium* sp., which has recently been authorised for commercialisation in the EU as a novel food ingredient [12]. Maximum use level of oil from *Schizochytrium* sp. (ATCC PTA-9695) depends on the food category where the oil is introduced and ranges between 80 and 600 mg/100g for non-alcoholic beverages (including dairy analogues and milk-based drinks) and spreadable fat and dressings, respectively [13]. Astaxanthin obtained from *Haematococcus pluvialis* is another example of microalgae-derived compounds currently being commercialised for food applications. This product is recognised as GRAS, which is the acronym for the phrase "generally recognised as safe", by the US Food and Drug Administration (FDA) [14]. The current review will focus on those products that contain the whole microalgal biomass as an ingredient. Table 1 lists several microalgae-containing foods that are currently being commercialised. Most of these products contain either *Spirulina* or *Chlorella*, mainly because of their long history of use. For example, in the EU, microalgae must be commercialised under the Novel Food Regulation (EU) 2015/2283, which aims at facilitating that businesses can bring novel and innovative foods to the EU market easily but maintaining a high level of food safety for European consumers [15]. According to this regulation, a novel food is defined as food that has not been consumed to any significant degree in the EU before 15 May 1997. Because of their long history of use, the access to the market of *Spirulina* and *Chlorella* is not subject to this regulation. Both species are also recognised as GRAS by the FDA. Novel foods containing biomass from other microalgae species will soon reach the European market. Indeed, the previously mentioned product *Plancton Marino Veta la Palma*® (Fitoplancton Marino S.L., Spain), which is the dried biomass of *Tetraselmis chuii*, has been recently authorized by the European Food Safety Authority (EFSA) to be marketed as a Novel Food in accordance with Article 3(1) of Regulation (EC) No 258/97 [16].

Foods containing microalgal biomass can be further divided into those that use microalgal biomass just as a colouring agent and those that use microalgae as a distinctive ingredient because of their nutritional or functional properties or as a marketing strategy – some of these are shown in Figure 1. Incorporation of microalgal biomass into the recipe of traditional food products, such as bread, is a global trend, as several products have been launched all around the globe. For example, British consumers can buy “Mavericks greenzilla breadsticks” (Maverick Makers Snacks Ltd., England), which contain 2% *Spirulina*, and the Malaysian company Lee Biscuits Ltd. currently commercialises “Spirulina filled crackers”. Other examples are listed in Table 1. The majority of the products listed in Table 1 are being commercialised in Europe (mainly Italy, Germany, Spain, and France), Asia, and North America. Not only the majority of the food products launched into the market but also the global algae-derived products market during 2017 was dominated by Europe, and this same trend is expected in the coming years [17]. Overall, most of the products currently being commercialised contain *Spirulina*. The very low concentrations used in some products suggest that microalgal biomass is used as a colouring agent or for marketing purposes, rather than for the potential nutritional or technological advantages of utilising microalgae as a food ingredient. Indeed, several products label *Spirulina* or *Chlorella* as a colorant. Moreover, the majority of the microalgae-containing products currently available are focused to vegan consumers, as well as consumers who decide to purchase organic or ecologic products. Indeed, the majority of the products commercialised in the EU, which are listed in Table 1, feature the EU Green Leaf logo, which indicates that the product is in full conformity with the conditions and regulations for the organic farming sector established by the EU: at least 95% of the agricultural ingredients are organic. Due to the rising demand for microalgal biomass and microalgal-derived products, not only for food applications but also in cosmetic, nutraceutical, pharmaceutical industries, among other uses, the recently published Credence Research market report predicted that the global market for algae-based products, valued at US$ 32.6 Bn in 2017, would reach US$ 53.4 Bn by 2026 [17].

Moreover, the global *Spirulina* and *Chlorella* markets were predicted to have an estimated value of US$ 2.0 and 0.7 billion by 2022, respectively [6].

3. Baked goods

The main advantages of using baked goods as delivery vehicles for health-promoting compounds is their widespread consumption and that they are generally encouraged as part of a healthy diet [18]. Moreover, baked products, such as bread, crackers, or biscuits, are not usually exposed to high pressures or strong pH variations and have been effectively used as food vehicles for health-promoting compounds, such as carbohydrates and proteins [19, 20]. Baked products containing microalgae are currently commercially available, some of them are listed in Table 1. Several scientific publications evaluated the effect of incorporating microalgal biomass into baked products. The current section summarises recent findings on the effect of microalgae incorporation into baked goods on their overall quality and on their sensorial properties.

3.1 Bread

Microalgae have been generally introduced into bread formulations to increase their protein content. For example, Achour et al. [21] aimed at increasing the protein content of bread by using *Spirulina* sp. biomass, obtained from nutritional supplements commercialised as pellets. *Spirulina* sp. incorporation, at concentrations ranging from 1 to 3%, resulted in increased protein content, which varied from 8.18% in the control white bread to 9.9% in the bread containing *Spirulina* sp. at a concentration of 3% ($p<0.05$). The authors observed that microalgae incorporation at both concentrations significantly decreased the bread's volume. Moreover, Figueira et al. [22] developed a gluten-free bread, made with rice flour, enriched in *Spirulina platensis* at concentrations ranging from 2 to 5%. In that study, the authors observed that concentrations under 4% did not affect the breads specific volume and textural properties. However, a 22% decrease in volume and a 113% increase in hardness were obtained after incorporation of the microalgal biomass at a concentration of 5%. In terms of nutritional value, the main outcome obtained after incorporation of microalgae into the bread formulation was an approximately 40% increase in the product's protein content. Figueira et al. [22] reported no differences in the sensorial properties of two breads containing *Spirulina platensis* at concentrations of 3 or 5%, assessed by 36 panellists under red lighting (sensorial properties of the breads were not compared against a control wheat-only bread). Most of the studies carried out to date evaluated the inclusion of *Spirulina* into bread and only a limited number of studies utilised different species. For example, Graça et al. [23] recently studied the impact of introducing *Chlorella vulgaris* on the rheology of wheat flour dough and bread textural properties and concluded that incorporation of the microalgae at concentrations up to 3% produced a positive impact on dough rheology and viscoelastic characteristics. However, the authors of that study reported that higher microalgae concentrations resulted in negative effects, not only on dough rheology but also on bread texture and flavour.

One of the main factors limiting the application of microalgae in baked goods is their green colour, which is not generally associated with bread. Visual cues modify the perception of taste, odour, and flavour and a well-known phrase among chefs is "you eat with your eyes first" [24]. In order to avoid the green colour of microalgae in baked products, a good alternative would be to isolate microalgae-derived proteins and to use them instead of the whole biomass. To the best of the authors' knowledge, there are no published studies assessing the flavour of breads containing microalgae-derived proteins. However, in a study published by Fitzgerald et al. [25], who conducted a sensorial analysis of a bread enriched in an enzymatic hydrolysate of the macroalgae *Palmaria palmata* (with antihypertensive properties) at a concentration of 4%, the authors reported a bitter taste of breads containing the algal-derived proteins. Results reported by Fitzgerald et al. [25] confirmed that the bioactivity of the enzymatic hydrolysate was resistant to the baking process. Similar results were reported by Lafarga et al. [26], which supports the hypothesis that bread is a suitable food delivery vehicle for healthy compounds.

Overall, results suggest that microalgal biomass can be effectively incorporated into bread formulations to obtain high quality products. Most of the studies published to date reported an increase in the protein content of breads after incorporation of microalgal biomass into their formulations. Moreover, most of the studies incorporating microalgae at concentrations higher than 3% reported technological limitations such as decreased loaf volume or negative sensorial attributes. Decreased loaf volume after incorporating microalgae into bread formulations can be attributed to a dilution of starch and gluten after substituting flour with microalgae and a decrease in the amount of fully hydrated starch granules caused by the added dried biomass competing for water with starch. It is important to select not only suitable microalgae concentrations but also to optimise mixing and proofing times to achieve suitable specific volumes (which can be correlated with textural attributes) of microalgae-containing breads.

3.2 Other baked goods

Cookies or biscuits, crackers, and pastries contain high percentages or sugar and/or fats relative to flour and these are generally separated from bread in the group of baked products. One of the advantages of biscuits or crackers when compared to bread is that their lower moisture content confers them with a longer shelf-life. Moreover, as mentioned previously, incorporation of high concentrations of an ingredient in bread generally lowers key attributes such as volume. However, volume is not as important as in bread for these products. For example, the maximum content of freeze-dried broccoli that could be incorporated into bread, without negatively affecting its overall acceptance was 2% [27], while the same ingredient could be incorporated by up to 15% in baked crackers without affecting their overall acceptance [19]. Several baked goods containing microalgae have been developed over the last years. For example, Rabelo et al. [28] formulated doughnuts enriched with *Spirulina platensis* biomass at concentrations ranging between 2.6 and 5.4% and obtained an improved nutritional quality (protein, mineral, fibre, and lipid composition) together with a good acceptance of the product. Moreover, Batista et al. [29] evaluated the potential of the microalgae *Spirulina platensis*, *Chlorella vulgaris*, *Tetraselmis suecica*, and *Phaeodactylum tricornutum* to improve the functional properties of cookies. Microalgae were introduced into the formulations at concentrations of 2 and 6%, shown in Figure 2. In that study, cookies prepared with *Spirulina platensis* and *Chlorella vulgaris* showed a higher protein content while all the microalgae-containing cookies showed a higher phenolic content and antioxidant activity when compared to the control. Moreover, *Spirulina platensis* was preferred by consumers: 22% of the panellists "would certainly buy" the cookies, while 46% "would probably buy" them. Similar results were recently observed by Sahni et al. [30], who formulated cookies containing defatted microalgae meal of *Chlorella* sp. at different concentrations and reported no differences in sensorial attributes at flour substitution levels under 6%. Cervejeira Bolanho et al. [31] enriched cookies with *Spirulina platensis* at a concentration of 5% and reported a 64 and 37% increase in the total phenolic content as well as in the antioxidant activity, respectively, of the microalgae-enriched cookies when compared with the control. The authors of that study also detected a 20% increase in the protein content. Similar results were reported by Hossain et al. [32] after incorporating *Haematococcus pluvialis* into cookies. Microalgae are not only rich sources of proteins and polyphenols but also of polyunsaturated fatty acids (PUFAs), such as eicosapentaenoic acid (EPA), docosapentaeonic acid (DPA), and DHA. Gouveia et al. [33] produced traditional butter biscuits enriched with *Isochrysis galbana* and reported a

PUFAs content (EPA+DPA+DHA) of 100 and 320 mg/100 g for biscuits enriched using *Isochrysis galbana* at 1 or 3%, respectively. The authors of that study also reported enhanced texture properties of microalgae-containing biscuits when compared to the control. Colour stability is an important parameter for foods containing natural pigments, which are not as stable as their synthetic counterparts [34]. However, the colour stability of foods containing microalgae seems to be very high. Gouveia et al. [35] used *Chlorella vulgaris* as a colouring agent in butter cookies and observed an increase in firmness, evidenced with an increase in microalgal biomass concentration, and a stable green colour of the cookies during a 3-month storage period at room temperature. Similar results were observed by Fradique et al. [36] and Gouveia et al. [33].

Overall, most of the papers published so far aimed at increasing the protein or the PUFAs content of baked products. Microalgae seem to be a promising ingredient not only in breadmaking but also for developing other baked goods, e.g., commercially available baked goods containing microalgae are listed in Table 1.

4. Beverages and dairy products

The main functional beverages currently commercialised can be divided into three groups, which include dairy-based beverages, vegetable- and/or fruit-based beverages, and sports or energy drinks [37]. Beverages are the most active functional foods category because of convenience and ease of distribution. Beverages are especially well suited as delivery vehicles for infants and the elderly. One of the main concerns for the elderly is the high incidence of protein deficiency within this portion of population. Increasing protein intake above the recommended dietary allowance can improve wound healing, blood pressure, bone health, and neurological function [38]. Ageing is associated with insufficient intake of proteins and, therefore, the potential for developing protein-rich functional foods for the elderly is ever increasing [39]. Microalgae have been suggested as a potential ingredient in the manufacture of protein-rich foods for the elderly. Indeed, Santos et al. [40] developed a shake-type chocolate flavoured powdered food enriched with *Spirulina* sp. at a concentration of 750 mg/100 g. Despite the low *Spirulina* sp. content, the protein content of the product increased from 41.3 to 43.4% after the incorporation of the microalgal biomass. Regarding the sensorial analysis, both the control and the microalgae enriched shake showed relatively high acceptance scores, reported as 7.9 and 7.6, respectively (assessed using a 9-point hedonic scale). In both cases, the acceptance was higher than that of a commercially available product. One of the main advantages of incorporating microalgae into juices, shakes, smoothies, or other beverages is that these products are generally coloured and consumers of these products demand for healthy and natural flavours or ingredients. Indeed, some of the major trends in beverages and concentrates during 2018 were plant-based products, products free from preservatives, products with a reduced sugar content, and products enriched in health-promoting ingredients such as vitamins or minerals [41]. Microalgae-containing plant-based soups and beverages have been also formulated. For example, Castillejo et al. [42] studied the quality changes of smoothies prepared containing several algae including macroalgae and the microalgae *Chlorella vulgaris* and *Spirulina* spp. (at a concentration of 2.2%) as well as grapes, broccoli, and cucumber. Smoothies containing *Spirulina* spp. showed the highest overall quality scores, while *Chlorella vulgaris* showed the lowest overall quality score on processing day, mainly due to a stronger marine odour and flavour. All of the smoothies showed overall quality scores over the limit of acceptability after storage at 5 ºC for 14 days. Moreover, Lafarga et al. [43] recently formulated a broccoli soup enriched in *Spirulina* sp., *Chlorella* sp., or *Tetraselmis* sp. at concentrations ranging from 0.5 to 2.0% (Figure 5) and assessed the effect of microalgae incorporation on the physicochemical and sensorial attributes of the soups. The main advantage of incorporating microalgal biomass into broccoli soup is that this product is naturally green. In that study, colour attributes of the soups were affected by microalgae concentration and specie and sensorial analysis revealed that consumers preferred soups with a lighter and greener colour. Microalgae incorporation into the soups also led to increased viscosity, antioxidant capacity, and phenolic content (as well as higher content of bioaccessible polyphenols). Moreover, the acceptability index of the soups formulated using lower microalgae concentrations was over 70% and their purchase intention ranged between 3.4 and 4.1 (assessed using a 5-point hedonic scale) suggesting that the soups would be well accepted.

Except for infant formula enriched in DHA and EPA, milk and dairy products are not commonly used as delivery vehicles of microalgal biomass or microalgae-derived compounds. As it happens with many other foods, consumers are not used to consume coloured dairy products, except for strawberry or vanilla milkshakes or yoghurts, which are associated with reddish and yellowish colours. Recently, Isleten Hosoglu [44] characterised the aroma of five microalgae species and identified a large amount of sulphur compounds, which were the main contributors to the perceived aromas of microalgae. The author of that study suggested that although the aroma of these compounds can be highly appreciated in certain foods such as toasted bread or cheddar cheese, microencapsulation or addition of flavourings should be used to improve the sensory attributes of foods enriched in microalgae. Indeed, Robertson et al. [45] manufactured a yoghurt enriched in lipids obtained from *Pavlova lutheri* and although the product contained an increased omega-3 content and that the incorporation of lipids into the formulation had no effect on the functional properties of the yoghurt, sensory analysis revealed that the fortified product was not well accepted. In that study, colour changes (reduced lightness and increased greenness and yellowness) were associated negatively with sensory properties.

5. Other food products

5.1 Snacks

A very interesting and complete study was recently published by Lucas et al. [46], who developed snacks enriched with *Spirulina* at a concentration of 2.6% and evaluated them with respect to their nutritional content, physical and microbiological properties, and sensorial characteristics. Overall, the authors of that study observed an increase in the content of proteins (22.6%), lipids (28.1), and minerals (46.4%) after incorporation of *Spirulina*. Moreover, flavour, texture, taste, and overall acceptance were not affected by *Spirulina* sp. and the sensory acceptance index of the snack containing *Spirulina* was 82%, suggesting a high overall sensorial acceptance. A photograph of the snacks formulated by Lucas et al. [46] can be seen in Figure 3. Moreover, Tańska et al. [47] compared the quality of corn extrudates made from corn grits with the addition of *Spirulina* up to concentrations of 8% (Figure 4). The authors of that study reported an average 0.6% in the protein content of the extrudates with each 1% increase in *Spirulina* sp. concentration. In that study, the highest overall acceptance score was noted for the control extrudates and its value decreased with increased *Spirulina* sp. incorporation. However, the acceptance of the extrudates containing *Spirulina* sp. was high, and was calculated as 4.7, 4.4, 4.2, and 4.0 (using a 5-point hedonic scale) for samples containing 2, 4, 6, and 8% *Spirulina*. The most diminished features were colour and crispness.

5.2 Pasta

Pasta products are largely consumed worldwide because of their sensory attributes, low cost, and ease of preparation. Several ingredients have been used to enhance the nutritional and functional properties of pasta, and these include microalgae. For example, Rodríguez de Marco et al. [48] developed pasta formulated with an increasing amount of *Spirulina* sp. biomass from 5 to 20 % and evaluated the technological and nutritional quality of the dried product. The authors of that study reported that only pasta formulated with *Spirulina* sp. at a concentration of 20% showed modified technological quality. Incorporation of *Spirulina* resulted in an increased total phenolic and protein content, although protein digestibility decreased with increased microalgae concentration. Similar results were observed by Zouari et al. [49], who reported an increased antioxidant capacity of pasta containing *Spirulina platensis* at concentrations ranging between 1 and 3%. Moreover, Fradique et al. [10] incorporated both *Chlorella vulgaris* and *Spirulina maxima* in spaghettis at concentrations of 0.5, 1.0, or 2.0% and reported increased quality parameters, such as firmness or protein content. Sensorial analysis revealed that the pastas containing microalgae had higher acceptance scores when compared to the controls. In a different study, Fradique et al. [36] manufactured spaghettis containing *Isochrysis galbana* and *Diacronema vlkianum* biomass at concentrations of 0.5, 1.0, or 2.0% to increase their content in EPA and DHA. The authors reported an increase in EPA and DHA content with increased microalgae concentration in both raw and cooked spaghettis and that the fatty acid profile presented a high resistance to cooking. Despite using the same microalgae concentrations as in the study of Fradique et al. [10], in this study, the panellists showed preference for the control pasta. As both *Isochrysis galbana* and *Diacronema vlkianum* are marine species, the panellists identified a fishy taste and the authors of the study suggested that fish based culinary preparations could take advantage of this issue. Selection of a suitable delivery vehicle is of key importance as, for example, Robertson et al. [45] formulated a high quality yoghurt enriched in PUFAs using a lipid extract from the microalga *Pavlova lutheri* and observed that supplementation of the yoghurt contributed to poor sensorial acceptability, despite the minimal impact on other functional properties of the product.

Overall, pasta products containing microalgae showed improved nutritional and functional properties, except for those containing high (20%) microalgae concentrations. Formulated products showed increased protein content as well as high concentration of EPA and DHA and good acceptability scores. Several studies highlighted the fishy taste of microalgae, especially of marine species. However, this could be an advantage rather than a problem, depending of the end use of the product.

Conclusions

Although the incorporation of microalgal biomass into traditional products found several challenges in the past, mainly because of their intense colour or their fishy taste and odour, several studies demonstrated that microalgae can be incorporated into food products with high physicochemical, nutritional, and sensorial quality. Yes, the most popular way to consume microalgae continues to be as a nutritional supplement in tablet, capsule, or powdered form. However, this trend is slowly changing and the current paper lists several currently commercialised products containing microalgae biomass launched into the market during the last years. Microalgae can be seen as a novel or trendy ingredient, but this valuable resource has potential to become a staple food for consumers all over the planet. Further research is needed to realise the full potential of these valuable resources as food, but results suggest a bright future for microalgae in the food industry.

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Author contribution

T. Lafarga searched literature, analysed and interpreted the results, and designed and wrote the article.

Statement of informed consent, human/anima rights

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Figure legends.

Figure 1. Commercially available microalgae-containing foods

Selected products containing *Spirulina* sp. include: (i) Chocolate 70% (The Algae Factory, the Netherlands, https://www.thealgaefactory.com/); (ii)* Zitronen zauber (Lubs, Germany, https://www.lubs.de/en/); (iii)* Spirulina filled crackers (Lee Biscuits, Malaysia, https://www.leebiscuits.com/); (iv)* Extreme green smoothie (Happy Planet Foods, Canada, https://www.happyplanet.com/); (v)* Greenzilla breadsticks (Maverick Makers Snacks, UK, https://www.mavericksnacks.com/); (vi)* Gullón Vitalday (Galletas Gullón, Spain, https://www.gullon.es/en/); (vii)* RAW BAs (Simply Raw, Germany, https://www.simplyraw.de/); and (viii) Kale and Spirulina pate (Sol Natural, Spain, https://www.solnatural.bio/).

Moreover, products containing *Chlorella* sp. include: (i)* Algen Crackers (Evasis Edibles, Austria, https://hellohelga.com/helga_english/); (ii)* Frecious slow juice (Frecious, the Netherlands, https://www.frecious.bio/nl/); (iii)* Algen Superfood (Evasis Edibles, Austria, https://hellohelga.com/helga_english/); (iv)* Chlorella fudge (Majami, Poland, http://www.majami.pl/en); (v) Super Gigg bar (Greenic, Germany, https://www.greenic-bio.de/); (vi)* Organic puffs (SC Honest Fields Europe, Romania, http://www.honestfields.com/); (vii) Orange and Chlorella bites (Grupo Dulcesol, Spain, http://www.dulcesol.com/); and (viii) Vichyssoise with Chlorella (Vesana Superfoods, Spain, http://www.vesana.es/).

* Additional information of these products is shown in Table 1.

Figure 2. Cookies containing microalgae at 2 or 6% (w/w)

Figure reprinted from Batista et al. [29] with permission from Elsevier.

Figure 3. (a) Control snacks and (b) snacks enriched with *Spirulina* sp. at a concentration of 2.6%

Figure reprinted from Lucas et al. [46].

Figure 4. Cross-section of extrudates containing *Spirulina* sp. at concentrations ranting from 0 to 8%

Images are cross sections of (a) control extrudates containing no microalgae and extrudates with (b) 2%, (c) 4%, (d) 6%, and (e) 8% of *Spirulina* and (f) 8% of *Spirulina* and 2% of baking powder. Figure reprinted from Tańska et al. [47].

Figure 5. Broccoli soups containing *Spirulina* sp., *Chlorella* sp., or *Tetraselmis* sp.

Abbreviations: CK: Control broccoli soup. S1–S4: Broccoli soups enriched in *Spirulina* sp. at concentrations ranging from 0.5 to 2.0% (w/w). C1–C4: Broccoli soups enriched in *Chlorella* sp. at concentrations ranging from 0.5 to 2.0% (w/w). T1-T4: Broccoli soups enriched in *Tetraselmis* sp. at concentrations ranging from 0.5 to 2.0% (w/w). Figure reprinted from Lafarga et al. [43] with permission from Elsevier.

Figure 1.

Spirulina
THE ALGAE FACTORY
Chocolate 70%
3g SPIRULINA ALGAE
Lubs
ZITRONEN ZAUBER
LEE
Spirulina
FILLED CRACKERS
HAPPY PLANET
extreme GREEN fruit smoothie
MAVERICKS
Greenzilla breadsticks
gullón
Vitalday
AVENA ALGAS
20% PROTEIN RAWBA
SPIRULINA & LEMON
Kale y Espirulina
a las Finas Hierbas
BIO PATÉ VEGANO
SIN GLUTEN
Chlorella
Helga
ALGEN CRACKER
Vegan & Organic
ALGEN. SUPERFOOD.
45g
FRECIOUS
100% VEG
GLORIOUS GREEN
Helga
ALGEN. SUPERFOOD.
earth of eco
KRÓWKI BIO
z chlorellą
150 g
SUPER GIGG
BANANE, SESAM, KOKOS, CHLORELLA
HONEST FIELDS
MATCHA & LIME
Organic PUFFS
30 g
Dulcesol
Innova
Chlorella
Bocaditos NARANJA
con Algas, Salvado de Trigo, Soja, Avena y zumo de Naranja
VESANA
Vichyssoise ECO con Chlorella

Figure 2.

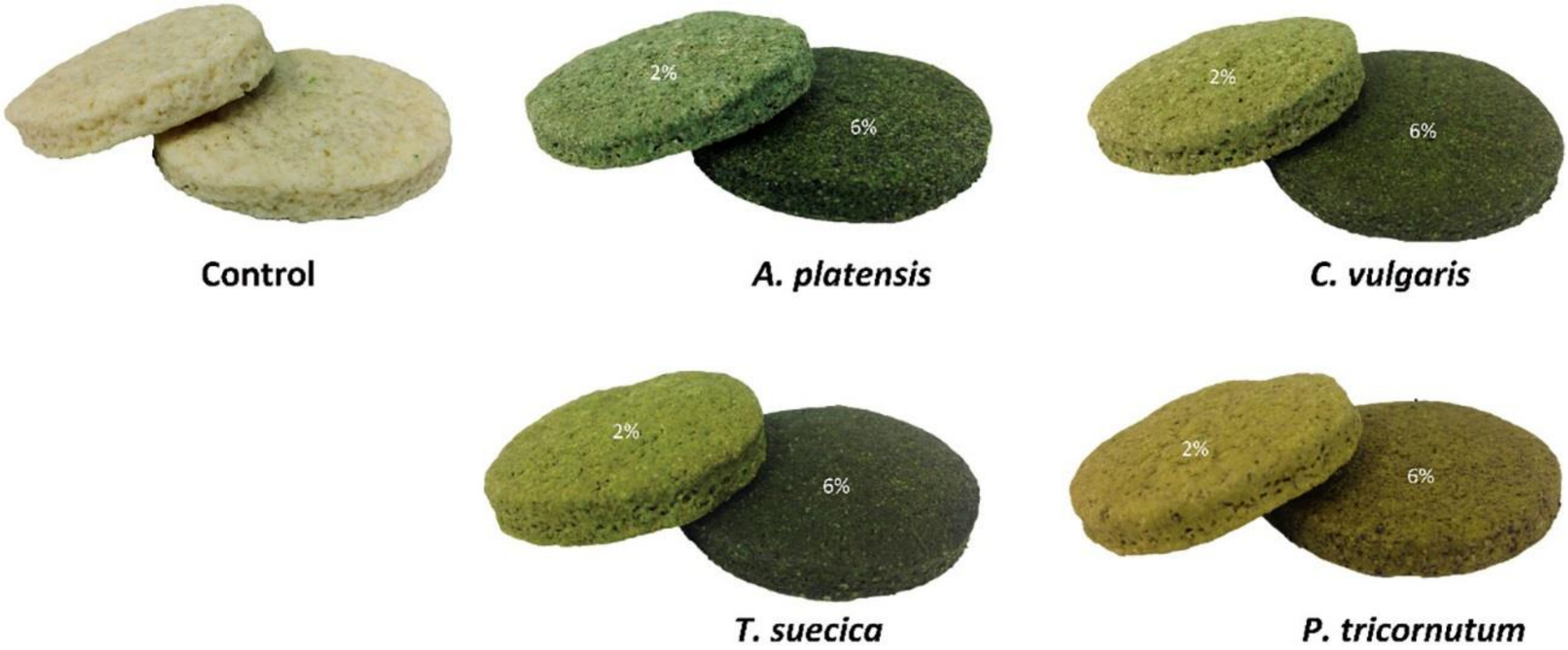
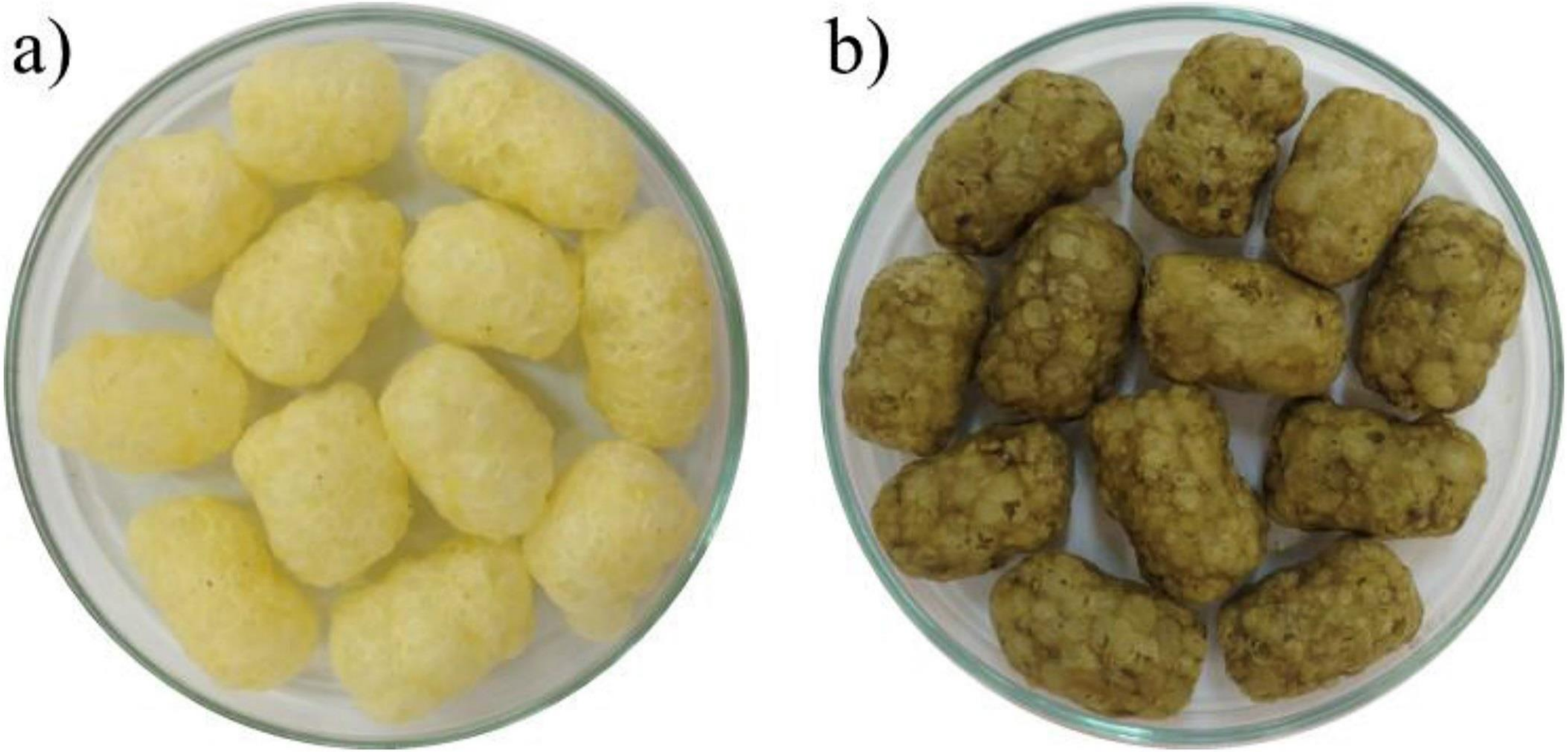

Control
2%
6%
A. platensis
2%
6%
C. vulgaris
2%
6%
T. suecica
2%
6%
P. tricornutum

Figure 3.



466 **Figure 4.**

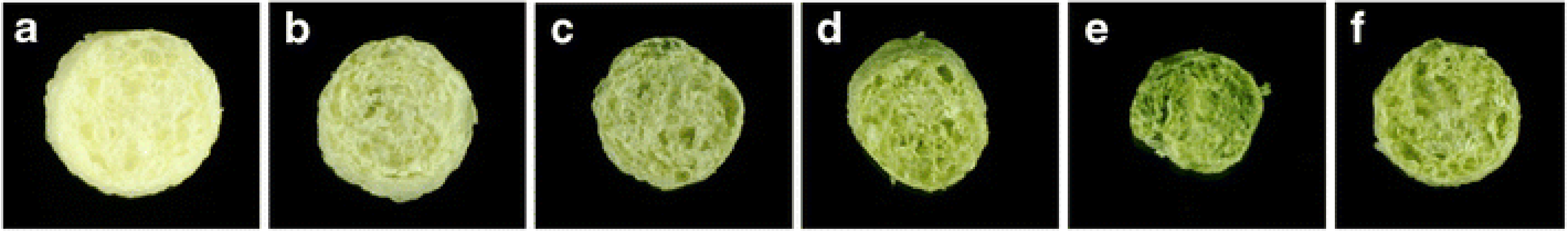
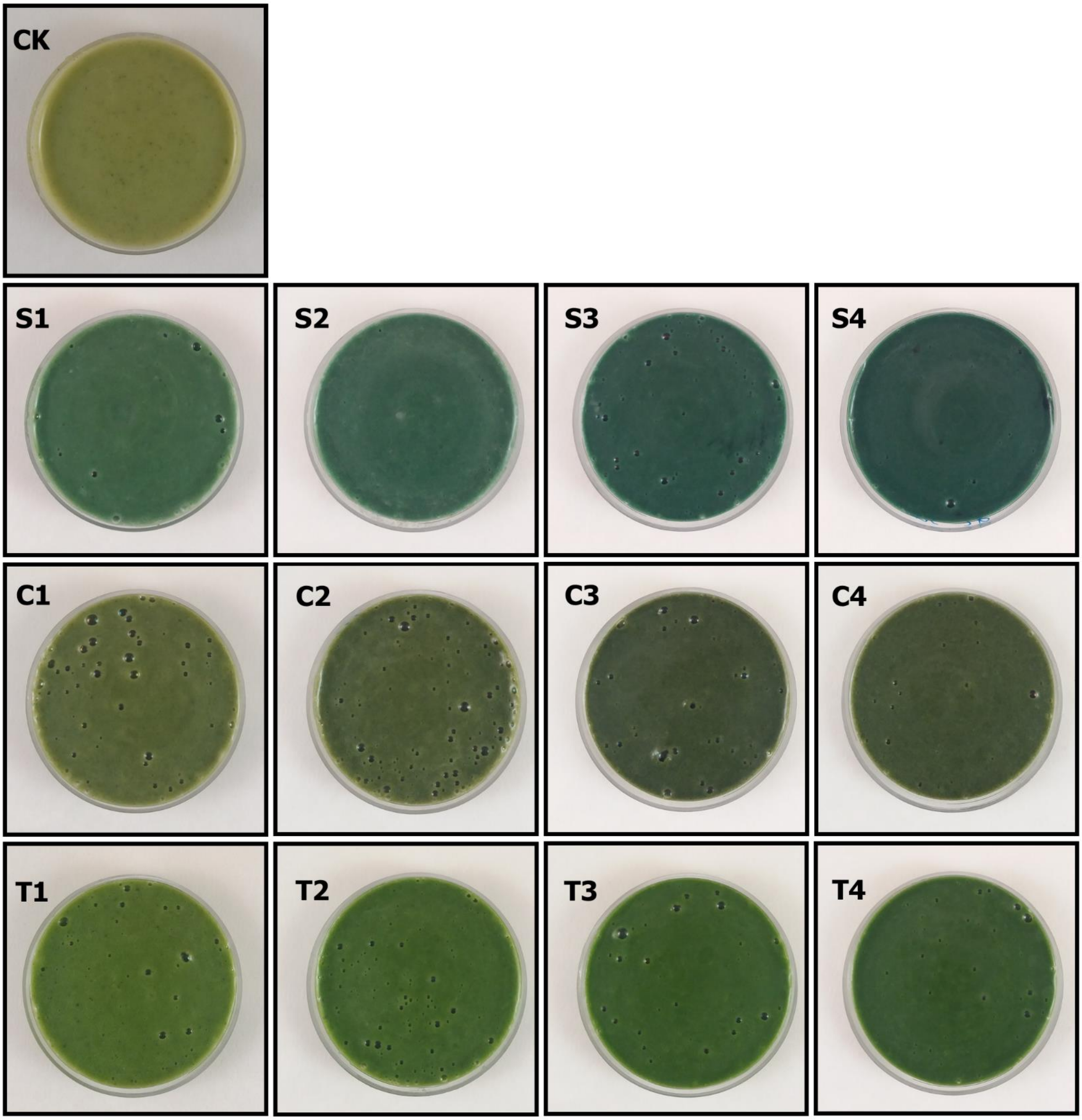


Figure 5



473 **Table 1. Currently commercialised products containing microalgae**

Brand	Company	Product description	Country of manufacture	Date published on MINTEL	Microalgae content	Additional information
Emmy's Organics	Emmy's Organics, USA	Mint chocolate-covered coconut cookies	USA	May 2019	N/A	Contains organic *Spirulina*
M&M's	Mars Wrigley Confectionery, Ireland	Chocolate hazelnut flavoured spread	Switzerland	April 2019	N/A	Contains *Spirulina* used as a natural colouring
Casino Bio	Casino, France	*Spirulina* and cranberry biscuits	France	April 2019	2.6%	Organic certified product bearing the AB and EU Green Leaf logos
Tic Tac	Ferrero Ibérica, Spain	Apple flavoured pastille mix	Portugal	April 2019	N/A	Contains *Spirulina*
Zebra Dream	Zebra Dream, Australia	Mint chocolate dairy-free coconut ice-cream	Australia	March 2019	N/A	Vegan product. Contains organic *Spirulina*
Zitronen zauber [a]	Lubs, Germany	Lemon chocolate truffles with *Spirulina*	Germany	March 2019	1.2%	Product on display at BioFach 2019 in Nuremberg, Germany

Helga [a]	Evasis Edibles, Austria	Organic algae drink	Austria	March 2019	0.2%	Bears the EU Green Leaf logo. Contains *Chlorella*
Helga [a]	Evasis Edibles, Austria	Sea salt flavoured seaweed crackers	Germany	February 2019	5%	Contains *Chlorella* (not seaweed).
Simply Raw Protein RAW BA [a]	Merlo's Best, Germany	Fruit bar rich in proteins with *Spirulina* and lemon oil	Germany	February 2019	5%	Features the EU Green Leaf logo
Oyá	Oyá, Germany	Organic smoothie with linseed and *Spirulina*	Germany	February 2019	N/A	Features the EU Green Leaf logo. Vegan product. Contains organic *Spirulina.*
Happy Planet [a]	Happy Planet Foods, Canada	Green fruit smoothie with *Spirulina* and *Chlorella*.	Canada	February 2019	N/A	Contains *Spirulina* and *Chlorella*
Winidoc Superfoods	Intoxicake, India	Superfood smoothie mix rich in antioxidants	India	February 2019	N/A	Contains *Spirulina*
Mavericks [a]	Maverick Makers Snacks, UK	Vegan breadsticks rich in fibre and free from added sugar	UK	February 2019	2%	Contains *Spirulina*

Lee [a]	Lee Biscuits, Malaysia	Crackers containing *Spirulina*	Malaysia	February 2019	N/A	Contains *Spirulina*
Próvida	Próvida Produtos Naturais, Portugal	Bio matcha and *Spirulina* biscuits	Portugal	February 2019	1%	Features the EU Green Leaf logo
Cesare Carraro	Incap, Italy	Green tea and *Spirulina* candies	Italy	February 2019	0.05%	Product displayed at the ISM 2019 in Cologne, Germany
OHi	OHi Foods, USA	Plant-based bar free from gluten, grains, and soy	USA	February 2019	N/A	Contains organic *Spirulina* and *Chlorella*
Frecious Slow Juice [a]	Frecious, the Netherlands	Vegetable juice containing *Chlorella*	The Netherlands	February 2019	2.4%	Bears the EU Green Leaf logo
Earth of Eco [a]	Majami, Poland	Organic fudge with *Chlorella*	Poland	February 2019	1.2%	Features the Bio-Siegel and EU Green Leaf logos
Tohato Harvest	Tohato, Japan	Crispy matcha biscuits	Japan	February 2019	N/A	Contains *Chlorella*
Honest Fields [a]	SC Honest Fields Europe, Romania	Smoked seaweed and sea salt organic puffs containing *Chlorella*	Romania	February 2019	N/A	Bears the EU Green Leaf logo

Gullón Vitalday [a]	Galletas Gullón, Spain	Oat and rice cakes with *Spirulina*	Spain	January 2019	1%	-
Healthy Tradition Gluten Free	Healthy Tradition, Ukraine	*Spirulina* and orange green granola	Ukraine	January 2019	2%	-
Better & Different	Better & Different, Israel	Peanut spread with *Spirulina*	Israel	January 2019	1.2%	Kosher certified suitable for vegans
Natali PotaBio	Nature et Aliments, France	Instant spinach and *Spirulina* soup	Spain	January 2019	1.5%	Features the AB and EU Green Leaf logo
Urban Remedy	Urban Remedy, USA	Blue coloured cashew milk containing *Spirulina*	USA	December 2018	N/A	USDA organic certified product
Ametller Origen	Casa Ametller, Spain	Vegan meatballs with spelt noodles and tofu	Spain	December 2018	20%*	Microwavable package
Nutrecentis di Ab	Agricultura Biologica, Italy	White corn and *Spirulina* pasta	Italy	December 2018	10%	-
Bottega Vegetale Alga Gurme	Bottega Vegetale, Italy	Vegetable burgers with olives and *Spitulina*	Italy	December 2018	1.5%	-

EcOriginal	Bionsan, Spain	Organic caramelised sesame with *Spirulina*	Spain	November 2018	N/A	Features the CCPAE and EU Green Leaf logos
Ginbis	Ginbis, Japan	Baked bean crackers in the shape of edamame beans	Russia	November 2018	N/A	Contains *Chlorella*
Lökki	Lökki, France	Organic kombucha with *Spirulina* and peppermit	France	October 2018	0.3%	Features the AB, EU Green Leaf, and Organic Fair Trade Bio Partenaire logos
Wickedly Prime	Amazon.com Services, USA	Sunflower seeds sprouted with Himalayan salt, spices, spinach and microalgae	USA	October 2018	N/A	Contains *Spirulina* and *Chlorella*
Tomy'z / Tomizawa / Tomiz	Tomizawa, China	Nori and wasabi coated peanuts	China	October 2018	0.07%	Contains *Chlorella*
Raw Sun Bite [a]	Lavica Food, Poland	Greens organic bar with *Chlorella* and *Spirulina*	Poland	May 2018	2% *Spirulina* and 1% *Chlorella*	Features the EU Green Leaf logo

* Contains noodles made with *Spirulina* at a concentration of 20%.

[a] Product shown in Figure 1.

Abbreviations: CCEAE, Catalan Council of Organic Production, EU, European Union; N/A, data not available; USDA United States Department of Agriculture.

Additional information: The EU Green Leaf logo is also known as “Euro-leaf” and indicates that the product is in full conformity with the conditions and regulations for the organic farming sector established by the EU (at least 95% of the agricultural ingredients are organic). The AB (Agriculture Biologique) logo was introduced in 1985 in France and certifies that a product fulfils the EU regulations for organic food. The Bio-Siegel logo is a German protected logo for organic foods and applies to organically farmed products and organic foods, which are partially processed in the European Community. ISM is one of the world’s leading trade fairs for sweets and snacks. FioFach is one of the world’s leading trade fairs for organic food. Data accessed on March 2019 from MINTEL, available at http://www.mintel.com/

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