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# Microalgae as a new resource in the food industry

***Elif Ceren ÇAKIROĞLU [1,a*], Güzin İPLİKÇİOĞLU ARAL [2,b]***

*1 Ankara University Institute of Health Sciences Department of Food Hygiene and Technology, Ankara, Türkiye,*
*2 Ankara University Faculty of Veterinary Medicine, Department of Food Hygiene and Technology, Ankara,Türkiye*

*0009-0001-5710-7402 [a]; 0000-0001-6897-8222 [b]*

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ABSTRACT:

The increasing global population, environmental pollution, energy consumption, and climate change have emphasized the need for sustainable food sources. Microalgae have emerged as an eco-friendly and sustainable alternative, with applications in food, pharmaceuticals, animal feed, biofertilizers, wastewater treatment, and bioenergy. With over 50,000 classified species, microalgae thrive in nutrient-rich waters, recycling nutrients while offering sustainable benefits like wastewater treatment and environmental improvement. Their high photosynthetic efficiency also supports biofuel and biomass production, promoting sustainable practices. Key microalgal species used in the food industry include *Arthospira platensis (Spirulina), Chlorella vulgaris,* and *Duniella salina*, cultivated globally for various applications. *Arthrospira platensis* contains up to 70% protein in its biomass, while algal species such as *Euglena gracilis* and *Chlorella vulgaris* contain up to 40% protein. Besides primary metabolites such as proteins, carbohydrates, and polyunsaturated fatty acids, microalgae produce secondary metabolites like pigments and phytosterols with known health benefits, supporting their use as functional foods. Microalgae cultivation is a sustainable approach to biomass production, characterized by its low land requirement, adaptability to non-arable regions, and high productivity. Its rapid growth rate and frequent harvesting potential make it a viable and resource-efficient alternative to conventional agricultural practices. Commercial cultivation began with *Chlorella* in Japan, followed by *Spirulina* in Mexico and *Duniella salina* in the U.S. for beta-carotene production. In India, cyanobacteria and *Haematococcus pluvialis* are used for astaxanthin. With high efficiency, cost-effectiveness, and adaptability, microalgae hold significant potential as a sustainable alternative food source for the future.

## *Gıda endüstrisinde yeni bir kaynak olarak mikroalgler*

ÖZET:

Artan dünya nüfusu, çevre kirliliği, enerji tüketimi ve iklim değişikliği, sürdürülebilir gıda kaynaklarına olan ihtiyacı vurgulamaktadır. Mikroalgler, gıda, ilaç, hayvan yemi, biyogübre, atık su arıtma ve biyoenerji gibi çeşitli alanlarda uygulamalarıyla çevre dostu ve sürdürülebilir bir alternatif olarak ortaya çıkmıştır. 50.000'den fazla sınıflandırılmış türüyle mikroalgler, besince zengin sularda gelişerek besinleri geri dönüştürürken, atık su arıtımı ve çevresel iyileştirme gibi sürdürülebilir faydalar sunar. Yüksek fotosentez verimliliği sayesinde biyoyakıt ve biyokütle üretimini destekleyerek sürdürülebilir uygulamaları teşvik eder. Gıda endüstrisinde yaygın olarak kullanılan temel mikroalg türleri arasında *Arthospira platensis (Spirulina), Chlorella* vulgaris ve *Duniella salina* bulunmaktadır ve bu türler dünya genelinde çeşitli uygulamalar için yetiştirilmektedir. *Arthospira platensis* biyokütlesinde %70'e kadar protein içeriği barındırırken, *Euglena gracilis* ve *Chlorella* vulgaris gibi türler yaklaşık %40 protein içeriği sunar. Mikroalgler, protein, karbonhidrat ve çoklu doymamış yağ asitleri gibi birincil metabolitlerin yanı sıra, pigmentler ve fitosteroller gibi sağlık açısından faydalı ikincil metabolitler üretir ve fonksiyonel gıda olarak kullanılmalarını destekler. Mikroalglerin yetiştirilmesi sürdürülebilir bir yöntemdir; daha az alan gerektirir, tarım için uygun olmayan bölgelerde yetiştirilebilir ve hızlı büyüme ile sık hasat avantajı sunar. Ticari üretim Japonya'da *Chlorella* ile başlamış, ardından Meksika'da *Spirulina* ve ABD'de *Duniella salina*'nın beta-karoten üretimi için kullanılmasıyla devam etmiştir. Hindistan'da ise siyanobakteriler ve *Haematococcus pluvialis* astaksantin üretimi için kullanılmaktadır. Yüksek verimliliği, maliyet etkinliği ve uyarlanabilirliği ile mikroalgler, geleceğin sürdürülebilir alternatif gıda kaynağı olarak büyük potansiyele sahiptir.

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* *Sorumlu Yazar e-posta adresi / Corresponding Author e-mail address: ecerencakiroglu@gmail.com*

## 1. Introduction

As the world population continues to expand, consumer demand for food also rises. Two billion people do not have sufficient access to nutritious food. As awareness of the relationship between food and population growth increases, alternative food sources are needed (1, 2). Global warming, increased environmental pollution and escalated energy consumption of energy causing significant problems worldwide. Climate change is also affecting agriculture (3). Microalgae are seen as a sustainable alternative food source for the growing population and insufficient food resources (4). Microalgae have many industrial applications such as pharmaceuticals, functional foods, animal and fish feed, cosmetics, chemicals and polymers, pollution control, bio-fertilisers, waste water treatment systems, bio-energy and many others (5).

The term algae is a polyphyletic grouping of a wide variety of organisms (6 ,7). The term microalgae refers to eukaryotic unicellular organisms and includes prokaryotic Cyanobacteria (6, 8).

The first unialgal cultures were obtained by Beijernick (1890) with *Chlorella* vulsynthetic gas exchangers for use as a microbial source of protein in space travel. The cultivation of *Chlorella* in Japan in the early 1960s led to a wide range of commercially available cultures. In the 1970s, a *Spirulina* harvesting and cultivation facility was established in Mexico. Later in the 1980s, over 1000 kg of microalgae per month were traded in Asia. From 1986, facilities were established in Australia and the USA to trade *Duniella salina* as a source of beta-carotene (9, 10). More recently, the production of *Haematococcus pluvalis* as a source of astaxanthin has been established in the USA and India. The biomass market for microalgae produces about 5000 tonnes of dry matter per year (8).

Besides high levels of primary metabolites such as protein, carbohydrates, polyunsaturated fatty acids and vitamins, secondary metabolites produced by microalgae are associated with beneficial health effects. Studies show microalgae as functional food with effective concentrations of various secondary metabolites including pigments, phytosterols and mycosporin-like amino acids (11).

Microalgae can be grown more quickly than other crops in terms of sustainability, and more frequent harvesting with a faster growth rate leads to an increase in overall productivity. Microalgae have the ability to adapt to different environments. As a result, microalgae production has a broader perspective and contributes to a reduction in land use. Their high photosynthetic efficiency makes them an important source for biofuel and biomass production. There are more than 50,000 classified species. They can grow in nutrient-rich waters and have the ability to recycle nutrients (2,12).

The entire biomass of some microalgae species has been incorporated into all foods for human consumption. The high quality metabolites obtained are more effective than synthetic alternatives in food applications due to their chemical structure. As food supplements and nutraceuticals, the concentration of metabolites contained in microalgae is higher than in other sources and has a positive effect on human health, and microalgae have gained a place in the food industry (8).

There are several species of microalgae that have been granted Generally Recognised as Safe (GRAS) status by the Food and Drug Administration (FDA). *Arthospira platensis, Chlamdomonas reinhardtii, Chlorella*, *Chlorella vulgaris*, *Dunaliella bardawill* and *Euglana gracilis* are among the species with GRAS status. GRAS only applies to the United States of America and differs from regulations in other countries. In the European Union (EU), the European Food Safety Authority (EFSA) oversees EU food regulations. *Haematococcus pluvialis, Odontella aurita, Schizochytrium spp., Tetraselmis chui* and *Ulkenia spp.* added to new EU food list. EFSA's risk assessment for the 2019 update of the list of biological agents added to food for Qualified Presumption of Safety (QPS) status includes *Aurantiochytrium limacinum*, *Euglena gracilis* and *Tetraselmis chui*. β-carotene from *Dunaliella salina* is also authorised for use as a food additive in the EU. *Dunaliella salina* is marketed as *Dunaliella* powder as a component of dietary supplements and functional foods for human consumption. *Chlorella* contains β-1,3-glucan, an active immune stimulator, a free radical inhibitor and a blood lipid lowering agent, which can also be used as a food additive and as a flavour modifier. *Chlamydomonas reinhardtii* is considered unsafe in Canada, Europe, Japan, India and China.

*Dunaliella bardawil* is also not considered safe in any of these countries, whereas *Dunaliella salina* is considered safe in China and Canada (7, 13).

## 2. Macro and Micro Nutritional Factors in Microalgae

Microalgae are a rich source of nutritional factors and bioactive compounds, including high value metabolites. They have positive effects on human and animal health. They also offer a sustainable and environmentally friendly alternative for potential food and feed applications (14).

Protein content varies between microalgal species. Genetic traits play an important role in determining protein content. Environmental factors also influence this variation. In general, 40-60% of microalgae dry matter can contain protein as demonstrated in Table 1 (15). The nutritional quality of proteins is usually determined by their amino acid composition. Most microalgae proteins consist of certain essential amino acids such as leucine, arginine and lysine, which make up 7% of the protein content. Other amino acids such as isoleucine, phenylalanine and threonine make up 4% of the protein content. Non-essential amino acids are amino acids such as aspartic acid and glutamic acid, which constitute 20% to 30% of the protein content (16). Mycosporine-like amino acids are involved in protection from salt stress and photosynthetic activities by stabilising osmotic pressure in microalgae. Mycosporine-like amino acids are found in approximately 152 species of microalgae and find important areas of use due to their potential benefits such as antioxidants and supporting cell proliferation (7) The amino acid content (g/100 g protein) and the amino acid profile of some proteins found in microalgae are presented in Table 2 (17).

**Table 1:** Protein content of some commercially important microalgae biomass.

***Tablo 1:*** *Bazı ticari açıdan önemli olan mikroalg türlerinin biyokütlelerindeki protein içeriği.*

| | **Average protein content % DW** | **References** |
|---|---|---|
| *Chlorella vulgaris* | 51-58 | 15 |
| *Dunaliella salina* | 57 | 18 |
| *Arthospira platensis* | 46-63 | 15 |
| *Aphanizomenon flos-aquae* | 62 | 19 |
| *Tetraselmis chuii* | 35-40 | 20 |

**Table 2:** Amino acid content (g/ 100 g protein) and the amino acid profile of some proteins found in microalgae.

***Tablo 2****: Mikroalglere ait bazı proteinlerin amino asit içeriği (g/100 g protein) ve amino asit profili.*

| | **Alanine** | **Arginine** | **Lysine** | **Tryptophan** | **Histidine** | **Phenylalanine** |
|---|---|---|---|---|---|---|
| *Chlorella vulgaris* | 10.82 ± 0.32 | 7.33 ± 0.21 | 5.35 ± 0.16 | 0.21 ± 0.01 | 1.52 ± 0.04 | 6.17 ± 0.18 |
| *Dunaliella salina* | 10.99 ± 0.32 | 8.16 ± 0.24 | 5.99 ± 0.17 | 0.18 ± 0.01 | 1.73 ± 0.05 | 6.98 ± 0.20 |
| *Arthospira platensis* | 11.48 ± 0.34 | 6.02 ± 0.18 | 7.11 ± 0.21 | 1.16 ± 0.03 | 2.19 ± 0.06 | 7.85 ± 0.23 |

The fatty acids found in microalgae contain higher levels of linoleic acid (C18:2) and alpha/gamma-linolenic acid (C18:3) than those found in commonly used vegetable oils. Phytosterols, similar to animal cholesterol but derived from microalgae, have anti-cancer, antioxidant, anti-inflammatory, anti-atherogenic and cholesterol-lowering properties. The phytosterol yield of microalgae including species such as *Pavlova lutheri, Tetrasellimis spp*. is high. The sustainability potential of microalgae as a source of phytosterols is higher when compared to other plants (21). Microalgae's lipid accumulation capacity has many potential uses. For example, various potential uses such as food, animal feed and food additives are being investigated (22).

The most abundant carbohydrates in microalgae are glucose, rhamnose, mannose and xylose. Hemicellulose and lignin are absent from microalgal biomass. The carbohydrate content of the biomass depends on the microalgal species and the environmental conditions. Microalgae typically contain high concentrations of carbohydrates, in excess of 50% of their dry weight. The specific composition of stored carbohydrates also varies between species. For example, Cyanobacteria produce glycogen (α-1,4-linked glucan). Green algae produce amylopectin-like polysaccharides (starch). Depending on their diversity, microalgae can be used for the production of biofuels and for different industries (23).

Microalgae are a potential source of a wide range of vitamins. *Dunaliella spp.* contains high levels of provitamin A and carotene, while *Chlorella spp.* contains three times the amount of carotene found in grass meal. According to studies, high levels of carotene, ascorbic acid and tocopherols are associated with *Dunaliella* spp. species and the carotene content can reach up to 1100 mg %. The efficiency and vitamin content of microalgae grown under open mass cultivation conditions are shown in Table 3 (7).

**Table 3:** Efficiency and vitamin content in microalgae that grown under the conditions of open mass cultivation (of absolute dried mass)

***Tablo 3:*** *Açık havuz sisteminde yetiştirilen mikroalglerin verimliliği ve vitamin içeriği (kuru ağırlık bazında)*

| | **Productivity ($g/m^2$ per day)** | **Carotene, mg%** | **Ascorbic acid, mg%** | **Tocopherol, mg%** |
|---|---|---|---|---|
| *Chlorella pyrenoidosa* | 22.0 | 220.3 | 68.5 | 25.2 |
| *Dunaliella salina* | 21.0 | 815.7 | 120.0 | 123.4 |
| *Euglena gracillis* | 18.0 | 137.0 | 182.7 | 67.8 |

Microalgae are important photosynthesizers and produce important pigments such as chlorophyll a, b and c, ß-carotene. The pigments contained in microalgae play an important role in photosynthesis and energy transfer processes. They also colour the organism. Environmental conditions such as temperature, light intensity and wavelength affect pigment production. Also, their adaptation to the environment, absorption spectra, ecological roles and various applications such as biotechnology and biofuels vary according to the pigments they contain. The main classes of pigments include chlorophylls, carotenoids and phycobiliproteins (24).

Phycobiliproteins are mainly found in Cyanobacteria. Although their spectral properties vary, phycobiliproteins can be analysed in four main groups as allophycocyanin, phycocyanin, phycoerythrin and phycoerythrocyanin. Phycocyanin extracted from *Spirulina* platensis is primarily used as a protein dye in the food industry. Phycocyanin is commercially known as lina blue and has fluorescent properties. *Phorphyridium aerugineum* produces a blue colour that is unaffected by pH changes. This property makes it important in the food industry. In particular, pigments extracted from *Phorphyridium aerugineum* are incorporated into beverages without heat treatment. Phycoerythrin has a yellow fluorescence (25). Microalgae contain one or more types of chlorophyll. The amount of chlorophyll they contain varies according to environmental conditions. For example, *S. platensis* contains only chlorophyll a. Chlorophyll a is used as a dye because of its stability. Microalgal species can accumulate 8-14% of their biomass from carotenoids. For example, in β-carotene-accumulating species of *Dunaliella salina*, astaxanthin accumulation is observed in addition to long-term exposure to UV radiation (26,27).

Lutein has food colouring, anticancer and antioxidant effects and covers approximately 4% of the dry weight in *Chlorella* spp. species. It can also be extracted from *Dunaliella salina* and *Muriellopsis spp*. microalgae species (28). The high antioxidant capacity of astaxanthin, a red coloured xanthophyll, which is the second most widely used microalgal carotenoid after β-carotene, is very important and has anti-inflammatory properties. It is used as a natural food colouring in both animal and human diets (29).

## 3. Uses of Microalgae in Food Industry

Microalgae can be used in various industries, from food to biofuel production. The use of microalgae in the renewable energy, biopharmaceutical and nutraceutical industries is increasing worldwide. Microalgae have multiple applications as value-added products in pharmacological and food formulation, feed production, cosmetics, fertilizers, wastewater treatment. Microalgae are considered to be a source of various bioactive compounds with antioxidant and anti-cancer properties, showing beneficial health effects. Their use in food formulations demonstrates the potential of microalgae as a new raw material for the food industry. The compounds are generally used in powder or tablet form. For example, *Arthrospira platensis* and *Chlorella* vulgaris are available as food ingredients in powder and capsule form (7, 30).

By 2050, the increase in total food consumption from animal sources is expected to lead to an increase in the global livestock population, resulting in an increase in greenhouse gas emissions from the livestock industry. According to FAO reports that methane emissions from ruminants, which are the largest source of greenhouse gases from agriculture, need to be reduced by 11-30 per cent by 2030 and 24-47 per cent by 2050 (31, 32). There are studies showing that microalgae can also be effective in this area. For example, Sucu's (33) study on the effect of adding *Chlorella vulgaris* and *C. variabilis* to diets on rumen fermentation showed that microalgae reduced methane production.

### Global production and market of microalgae

*Chlorella* and *Spirulina* have become globally marketed nutraceuticals. Major production centres are located in countries such as Australia, China, South Korea, Malaysia, Singapore, Taiwan, USA, Netherlands, Spain, Portugal, France, Denmark, Japan and several African countries. In particular, *Chlorella* and *Spirulina* have been incorporated into a variety of food products such as pasta, biscuits and juices in order to improve their nutritional profile. In addition, the use of *Spirulina* as a natural colour additive in foods has been approved by the FDA in the United States. *Arthrospira*, and more commonly *Spirulina*, are protein-rich microalgae that have been known and present in the human diet for thousands of years. Historical sources show that the Aztecs consumed a blue cake made from *Arthrospira*. In the food industry, the cultivation of *Arthrospira* began in Mexico in the 1970s, and commercial production of *Chlorella* began in Japan in 1952 (34).

### Microalgae in food and nutritional applications

*Spirulina* platensis is an important source of protein for malnourished people. Chocolate biscuits enriched with *Spirulina* platensis, as well as its addition to bread ingredients, have improved the protein content and digestibility of foods. In particular, *Chlorella* and *Spirulina* have been incorporated into a variety of foods, including noodles, cookies, nutritional bars and fruit juices, to improve their nutritional profile (34). Table 4 presents an overview of nutraceutical products formulated with microalgae or their components, along with their applications in different food and supplement forms (35).

*Isochrysis galbana* microalgae has been added to some foods to provide the effects of omega-3 polyunsaturated fatty acids. *Arthospira platensis* is added to increase the protein content of products. They are used to improve the nutritional and health benefits of snacks. *Dunaliealla sp.* and *Arthrospira* species are added to bread varieties, including gluten-free ones, to increase the protein content (3).

**Table 4:** Applications of microalgae in food, pharmaceuticals, and animal feed, and their use as fertilizers and biostimulants.
***Tablo 4:*** *Mikroalglerin gıda, ilaç ve yemlerdeki uygulamaları, gübre ve biyostimülan olarak kullanımı.*

| Bioactive Compound | Microalgae Source | Product Examples (Brand) | Manufacturers |
|---|---|---|---|
| Carotenoids | Dunaliella salina | Supplement – Patented Betatene® β-carotene | Cyanotech, Mera Pharmaceuticals, AstraReal AB, Jingzhou Naturals |
| Beta-carotene | Chlorella vulgaris | Supplements – Dr. Mercola, Chlorophyll-Fermented Chlorella, 450 Tablets | Mercola, Florida |
| Lutein | Chlorella pyrenoidosa | Terranova fresh freze dried Chlorella pyrenoidosa | Terranova Synergenistic Nutrition, UK |
| Protein & Vitamin B12 | Chlorella sp. | Food additives – Algal proteins or whole biomass | Sophie's BioNutrients, Singapore |
| Astaxanthin | Haematococcus pluvialis | Supplement – Max Botanics astaxanthin supplements/sunscree ns | Mera Pharmaceuticals, AstraReal AB, Jingzhou Naturals Astaxanthin Inc., Max Botanics UK & Europe |

Meat samples from broilers fed *Spirulina* platensis showed many positive effects, including longer shelf-life and increased antioxidant capacity with reduced lipid oxidation. In fatty acid profiles, increased levels of omega-3 fatty acids provide nutritional benefits in humans (37).

Microalgae such as *Chlorella vulgaris*, *Arthrospira platensis* and *Spirulina* are also used in aquaculture. Pigments are particularly important in maintaining flesh colour in species such as salmon, sea bream and koi/ornamental fish. Pigment supplementation, including carotenoids, has been observed to improve product quality in fish such as rainbow trout. For example, *Haematococcus pluvialis* is used to provide pigmentation (38).

Cattle were fed a diet containing microalgae to increase the levels of omega-3 polyunsaturated fatty acids, docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). The microalgae species *Schizochytrium* and *Nannochloropsis sp.* show that their cell walls prevent the omega-3 fatty acids in the algae from becoming unavailable in the small intestine after they have been dispersed from the rumen and hydronised. This has led to studies to increase omega-3 levels in beef production due to economic factors and consumer preferences (39).

Studies have shown the bioavailability of fatty acids such as PUFA and eicosapentaenoic acid (EPA) extracted from *Phaeodactylum tricornutum*, including fucoxanthin and its metabolites and β-carotene. In this case, *P. tricornutum* can potentially be a sustainable and valuable food source, as it can be a low-cost, nutrient-rich food. It has also been observed that *P. tricornutum* is richer in EPA and n-3 PUFA than fish (40). The incorporation of microalgae-based ingredients into various food products, such as baked goods, enhances their nutritional and techno-functional properties, as demonstrated in Table 5.

**Table 5:** Nutritional and techno-functional properties of microalgae-based formulated food products.

***Tablo 5:*** *Mikroalg bazlı formüle edilmiş gıda ürünlerinin besinsel ve teknolojik-fonksiyonel özellikleri.*

| Bioactive Compounds | Microalgae Source | Food Product | Reference |
|---|---|---|---|
| Chlorophyll-a and total carotenoids | *Isochrysis galbana* and *Nannochloropsis oculata* | Natural green colorant in chewing gum | 41 |
| Astaxanthin | *Haematococcus pluvialis* | Wholemeal cookies with enhanced antioxidant properties and reduced glycaemic response | 42 |
| High protein content (80%), iron (49.8 mg/100 g), polyunsaturated fatty acids (γ-linolenic acid - 13.8%), and pigments (chlorophylls, β-carotene, phycocyanin, allophycocyanin) | *Spirulina maxima* | Nutritionally enriched biscuits with improved protein, iron content, and sensory acceptance through spray-drying microencapsulation | 43 |
| High protein content (60–70%), vitamin B12, gamma-linolenic acid (GLA), calcium, iron, magnesium, chlorophyll-a, phycocyanin, and carotenoids | *Spirulina platensis* | Nutritionally enriched bread with *Spirulina platensis* (10% incorporation) | 44 |

## 4. Regulations

Although food safety is important for regulatory organizations worldwide, potential hazards associated with the consumption of algae-based food require assessment. Various nations, like the European Union and the USA, enforce specific laws for food products that contain microalgae (45).

There are some challenges in the marketing of microalgae-based products in the European Union, such as production costs, technological developments and regulatory compliance. Despite regulatory barriers such as climatic variability, limited consumer demand and the EU Novel Food Regulation, the EU is considered to have the potential to strengthen its market position in the coming periods. The share of microalgae products in the EU covers approximately 5 % of the global market (46).

Microalgae-based products used in the food industry are subject to food safety regulations, namely the European Community Food Safety Regulation (EC 178/2002). The placing on the market of food containing microalgae or microalgal ingredients is primarily governed by the Food Safety Regulation (EC 178/2002) and the suitability of algae for human consumption by the Novel Food Regulation (EC 2015/2283). For example, *Chlorella* vulgaris is not recognised as a novel food. However, it can be used as a food ingredient under the Novel Food Regulation (EC) 2015/2283. Under this regulation, health claims for food and feed must be generally recognised under (EC) 1924/2006. The European Food Safety Authority (EFSA), Panel on Nutrition and Allergies (NDA), carries out all scientific assessments of food and feed (46, 47).

In the USA, the Federal Drug and Cosmetic Act and the Dietary Supplement Health and Education Act apply to the use of microalgae. Generally Recognised as Safe (GRAS) status is granted by the FDA. GRAS status defines what is safe for human consumption. Certain microalgae species such as *Spirulina* spp., *Chlorella* spp., *Dunaliella spp., Haematococcus spp., Schizochytrium spp., Porphyridium cruentum* and *Crypthecodinium cohnii* have GRAS status. In addition, specific oils from *Schizochytrium* and Ulkenia and specific microalgal protein powder and lipid content from *Chlorella* spp. have been granted GRAS status in the USA (47, 48).

China and Japan are leading the way in creating sustainable market production for microalgae-based products, with Japan particularly focused on securing its energy supply through algae-derived biofuels. Algae consumption is more widespread in Asia than in Western countries. Consumers have been using algae for a long time. Additionally, the lower cultivation and labor costs in Asian nations, coupled with fewer regulatory constraints, are driving the rapid development of the microalgae industry across various sectors, including food, feed, and energy diversification (49, 50). In Japan, food safety inspections are overseen by the Minister of Health, Labour and Welfare, primarily through the Department of Pharmaceutical and Food Safety. The Basic Food Safety Act serves as the principal legal framework regulating food quality, supplemented by additional statutes such as the Food Sanitation Act (51). Microalgae-based products are subject to regulatory oversight under Foods with Function Claims (FFC) and Foods for Specified Health Uses (FOSHU), which encompass products containing bioactive components with scientifically validated physiological benefits and biological activities (52).

Although algae consumption is not widespread in our country, there is no food regulation in force. However, microalgae preparations as food additives are evaluated within the food categories specified in Annex-II Part D of the Turkish Food Codex Food Additives Regulation (53). In the legal legislation, the regulation for the Turkish Food Codex 'Regulation on plants, fungi, algae and lichens that can be used in foods' was submitted as a draft in 2022 and has not yet entered into force (54). Furthermore, the Turkish Food Codex Novel Foods Regulation remains in the draft stage and has not yet been officially published in the Official Gazette. Microalgae are classified as novel foods, necessitating comprehensive safety and quality assessments prior to market approval to ensure compliance with regulatory standards. This regulation establishes the framework for evaluating the safety of foods that have not been historically consumed on a significant scale. For instance, the regulation defines the usage conditions, specifications, and labeling requirements for β-glucan derived from *Euglena gracilis*. It mandates that product labels explicitly state "Beta-glucan (derived from *Euglena gracilis* microalgae)", while dietary supplements containing this ingredient must include consumption warnings tailored to specific age groups. These provisions are designed to facilitate the safe incorporation of microalgae-based ingredients into the food industry while ensuring transparent consumer information and regulatory compliance (55).

## 5. Challanges and Future Perpective

*Arthospira*, *Chlorella*, *Dunaliella salina*, and *Scenedesmus sp*. are the most common species utilized in the commercial cultivation of microalgae for the food industry. *Arthospira* produces 12,000 tonnes annually, *Chlorella spp.* 5,000 tonnes, and *Dunaliella salina* 3,000 tonnes (12). The United States, Asia, and Europe are engaged in the microalgae-based products market (56). Although the industry is expanding, the costs of producing and processing of microalgae limit their popularity as food alternatives, technological developments and automation may mitigate these challenges. Improvements such as strict contamination control, efficient energy use, and optimized harvesting techniques are essential for enhancing production. Additionally, addressing taste and odor issues, along with promoting eco-friendly products through public incentives and consumer awareness initiatives, is vital for the successful market integration of microalgae-derived foods (57).

Challenges exist in the production and processing of microalgae within the food industry. These include isues such as regulation, cost, and food safety. There are a number of strategies which are being developed in response to these challenges. These include taking measures to control contamination through the use of photobioreactors, improving microalgae production and processing stages, and developing more sustainable methods (44).

The production of microalgae can be categorized into two categories: open pond systems and closed cultivation systems, such as photobioreactor units (58). Open pond systems are cost-effective and suitable for fast-growing species; however, they are prone to contamination (59). Periodic inspection and monitoring are required. Furthermore, the quality of water utilized in biomass production must be examined for contaminants like heavy metals, pesticides, and antibiotics (60). Photobioreactors have advantages over open systems. These include the ability to utilise light more effectively, produce a high volume of biomass, have a low risk of contamination and water loss, facilitate gas transfer and incorporate mixing. In addition, the investment costs are higher. However, algae production in outdoor open ponds is cost-effective, but is only compatible with fast-growing species and is associated with risks related to climatic conditions (61).

In the production of microalgal biocultures, it is essential to detect potential hazards. Including biological, chemical, and physical risks. Critical points include the presence of naturally occurring toxins, contamination with heavy metals and levels of pathogenic microorganisms. For example, Arsenic (As) pollution and eutrophication in aquatic environments increase the risk of heavy metal contamination in edible microalgae, leading to potentially harmful effects in algal products. Limited studies have reported As levels in algae products; for example, the addition of 150 µg/L As(V) in to Zarrouk medium resulted in *Spirulina platensis* surprassing the Chinese National Standard for Health Functional Food (25). Hazard analysis is important in production to identify critical control points that require monitoring. Protocols established by regulatory organisations such as EFSA and FDA are important in ensuring the quality and safety of products (62).

Toxins found in microalgae are mainly domoic acid, pectenotoxins, microcystins, saxitoxin, okadaic acid, brevetoxin. In the study, no toxicity was observed when 10% of the algal biomass from C. protothecoides was included in the diet for 28 days. This supports the absence of toxicity at the highest No Observable Adverse Effect Level (NOAEL) dose tested (63).

Blue-green algaes (Cyanobacteria) are capable of producing toxins. Among these, anatoxin-a is a neurotoxin that known for its fast absorption and abilty to cause acute paralysis and respiratory collapse. These toxins can be contamine the algae-based dietary supplements, presenting significant public health risks. To address this issue, effecient water treatment methods are required to reducing toxin presence in recreational and drinking water sources (64). Also, *Spirulina* spp. and in particular *Aphanizomenon flos aquae*, are mainly used in the production of blue-green algae supplements (BGAS). However, these supplements can be contaminated with microcystins, presenting a significant health risk to consumers. The variability in contamination levels, even between batches of the same brand, and uncertainties about daily consumption, highlights the need for strict monitoring by BGAS producers and increased vigilance by health authorities to ensure consumer safety (65).

There is a potential risk of allergy associated with the consumption of microalgae-based products. While limited research exists on the frequency of allergenicity of edible algae species, some studies indicate high IgE activity specific to algae, while more research is needed on consumer exposure and potential contamination from seafood-related allergies (66). Particularly *Spirulina*, poses potential allergenic risks. Le et al., (67) reported a case of a 17-year-old male who experienced anaphylaxis after ingesting *Spirulina*, with skin prick testing confirming that the allergy was specific to the microalgae and not to its additives. Due to the increasing popularity of *Spirulina* as a dietary supplement, it is essential that comprehensive allergenicity risk assessments to determine the potential for cross-reactivity with known allergens prior to its widespread consumption.

Despite the potential health benefits of microalgae, their inclusion in food products is limited, mainly due to sensory concerns. There are sensory barriers in their daily use, especially in terms of colour and taste. Furthermore, processing and packaging technology advances, such as microencapsulation or nanoemulsion, offer opportunities for encapsulation of microalgae extracts, thus reducing their sensory impact while maintaining nutritional enrichment (68). Overcoming these organoleptic difficulties will be important to the effective incorporation of microalgae into conventional food products, thus revealing their potential health benefits and nutritional values (50).

Legislation and regulations related to food additives and innovative foods, including nutraceuticals and functional foods, differ between countries. Microalgae products intended for human and animal nutrition are subject to a range of regulations that affect production processes and labeling requirements, leading to potentially lengthy and costly market introduction processes. This regulatory complexity can result in protracted and expensive routes for introducing these products to the market (69). Challenges to the commercialisation of microalgae products in the European Union include biomass production costs, technology and regulatory compliances. Despite challenges such as climatic conditions and regulatory barriers, the microalgae industry has taken off in the European Union (56).

Advances in genetics are enabling the use of transgenic microalgae in bioactive production, and gene modification in various microalgae species is attracting attention. Transgenic microalgae expressing dsRNA have the potential for disease management by targeting specific pathogens (70).

Recent advancements in CRISPR-Cas systems have facilitated the genetic optimization of microalgae and cyanobacteria, enabling significant progress in various biotechnological applications. Cas9 and Cas12a (Cpf1) enzymes precisely target specific DNA sequences, thereby enhancing the efficiency of genome editing processes. Moreover, species such as *Chlorella*, *Phaeodactylum*, *Tetraselmis* have been successfully engineered using CRISPR technology for genetic modifications and enhanced lipid production. These developments significantly expand the biotechnological and industrial potential of microalgae (71). However, certain technical challenges, such as Cas9 toxicity, have limited the advancement of CRISPR-based genetic modifications in microalgae (72).

The work by Qv et al. emphasi the efficacy of microalgae-bacteria consortia (MBC) in the elimination of fluoroquinolone antibiotics and the horizontal transmission of resistance genes. The results highlight the importance of environmental monitoring and the role that transposons and integrons play in gene transmission. MBC-based therapies should be improved in future studies to increase effectiveness and prevent the spread of resistance genes (73).

## 6. Conclusion

Microalgae have great potential for various industries, from food to medicine, from animal feed to fuel, if produced on a commercial scale. Research and development studies on biomass production and processing of microalgae are also very important in terms of economic sustainability.

Microalgae-based products can play an important role in the food industry. With their high quality metabolites, they can contribute to the demand for various food ingredients. However, there are only a few microalgae-based products available on the market. Microalgae are produced as nutraceuticals and food supplements. To fully harness their potential, it is essential to improve social acceptance of microalgae-based foods. The provision of legal capacity will expand their use in the food industry. Again, as research into the use of microalgae in food is carried out, it is expected that the market for these products will develop.

Innovative design and technology should be developed to address the taste and odour problems caused by microalgae in food. There is a need for public incentives for the consumption of environmentally friendly products. Design is also important for market integration of foods containing microalgae. Support for innovative designs is important for the promotion of algae products. Consumer awareness programmes and the positive health properties of the products should be demonstrated.

Advanced design and technology must be developed to resolve the flavour and aroma issues associated with microalgae in food. Public incentives are necessary to promote the consumption of environmentally sustainable products. The design is crucial for the market integration of foods including microalgae. Advocacy for novel designs is essential for the advancement of algal products. Consumer awareness initiatives and the beneficial health benefits associated with the products should be demonstrated

In addition to the nutrient composition of microalgae and expand their utility in the food sector, biotechnological and genetic research should be undertaken to elevate their protein synthesis capabilities and reduce anti-nutritional factors. Advanced gene editing technologies, such as as CRISPR-Cas, are essential for enhancing the functional components of microalgae. Additionally, the advancement of flavour and odour neutralisation methods is crucial for enhancing the sensory qualities of microalgae-derived foods. Innovative technologies, such as microencapsulation and nanoemulsion, can enhance the flavour profiles of algal-based food products, hence improving their market acceptance.

Progress in genetic research facilitates the use of transgenic microalgae for bioactive synthesis, underscoring the significance of gene modifications across diverse microalgae species. The production of double-stranded RNA (dsRNA) by transgenic microalgae has possibilities for disease management through the targeted elimination of specific pathogens.

## Conflict of Interest

The authors declared that there is no conflict of interest.

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**Authors' Contributions**

Motivation / Concept: Elif Ceren ÇAKIROĞLU, Güzin İPLİKÇİOĞLU ARAL
Design: Güzin İPLİKÇİOĞLU ARAL
Control / Supervision: Güzin İPLİKÇİOĞLU ARAL
Data Collection and / or Processing: Elif Ceren ÇAKIROĞLU, Güzin İPLİKÇİOĞLU ARAL
Analysis and / or Interpretation: Elif Ceren ÇAKIROĞLU, Güzin İPLİKÇİOĞLU ARAL
Literature Review: Elif Ceren ÇAKIROĞLU, Güzin İPLİKÇİOĞLU ARAL
Writing Manuscript: Elif Ceren ÇAKIROĞLU, Güzin İPLİKÇİOĞLU ARAL
Critical Review: Güzin İPLİKÇİOĞLU ARAL

**Ethical Approval**

The data, information and documents presented in this article have been obtained within the framework of academic and ethical standards. Ethical statements have been obtained from the authors, affirming that all information, documents, evaluations, and conclusions are presented in accordance with scientific ethical and moral principles.

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