

AS A RESOURCE OF FOOD AND FEED:ALGAE

Abstract

Food supply security is at risk due to factors such as improper agricultural practices, increase in human population, soil and water pollution. To cope with this risk, the search for an innovative, sustainable and effective food alternative has arisen. Algae have been used as a food source for many years because they have the nutritional composition that is the basic need of a living thing. Algae contain macronutrients such as usable protein, fat and carbohydrates, as well as essential amino acids and fatty acids. They are also rich in vitamins, minerals and pigments with antimicrobial and antioxidant properties. Studies on algae, which can be used in many areas such as biofuel production, C capture, wastewater treatment, have begun to focus on the production of high-value molecules. In recent years, algae-based food products containing these high-value molecules have been designed and commercialized. These products have a significant place in the algal biotechnology market and all the countries of the world have started to realize this.

Algae have the potential to be used as human food as well as animal feed. Since algae contain more protein compared to traditional agricultural products and do not need to occupy agricultural land for their production, they are seen as a remarkable source of biomass in animal feed. In addition, intensive microalgae production for animal feed contributes to sustainable agriculture by absorbing the salinity and drought caused by the brutal use of agricultural lands, global warming by absorbing carbon, and preventing agricultural pollution by using nitrogen and phosphorus.

There are still some obstacles to the

Authors

FusunAkgül

Burdur Mehmet Akif Ersoy University
Fac. of Sci. and Arts Dep. of Mol. Bio. and
Genetic
Burdur, Türkiye
fakgul@mehmetakif.edu.tr

RızaAkgül

Burdur Mehmet Akif Ersoy University
Food, Agriculture and Livestock Vocational
High School
Burdur, Türkiye
rizaakgul@mehmetakif.edu.tr

use of algae as food and feed. however, when its economic return and efficiency are evaluated, it is clearly understood that they are the most important organisms for the prevention and overcoming of the food and environmental problems awaiting humanity in the future. Further studies are needed to optimize culture conditions, the effects of culture stress parameters on biochemical composition and molecular pathway studies, and to increase biomass productivity per unit volume. If algal biotechnology studies continue at the current pace, all these obstacles will be overcome in the next 10 years and the algal biotechnology market will have increased at least 3 times.

In this chapter, the potential of algae as food and feed, the current status of algal biotechnology applications in this field, their contribution to the economy and the environment, the obstacles in front of this sector and what needs to be done to overcome will be focused on.

Keywords: algae, biotechnology, cultivation, food, feed, nutrient, animal, sustainable

I. INTRODUCTION

The increase in drought and salinity of agricultural lands caused a decreasing arable land. Parallel to this, the increase in the human population has created the problem of food inadequacy around the world. Statistical studies show that one out of every 9 people is faced with malnutrition. Improper agricultural practices to get more products from the unit area increase this problem even more. For all these reasons, there is a need for alternative food sources that can reduce and even stop the negative effects on agricultural areas and at the same time meet the food needs of people. For this purpose, scientists have conducted studies in different fields and defined algae as a promising alternative food source of the future. When evaluated in terms of environmental impact, red meat consumption requires a lot of agricultural land and water use and causes a lot of greenhouse gas emissions. Conventional agriculture also causes soil erosion and contamination of surface and groundwater[1, 2].

In this section, the term "Algae" will be used to include prokaryotic cyanobacteria, eukaryotic one-celled microalgae, and macroalgae. Algae are photosynthetic organisms that use CO₂ and light to produce food and O₂ also they produce 50-87% of global O₂[3-5]. It is known that there are 80,000-100,000 different algae species that can use light as an energy source in their metabolic processes and live in fresh and salt water sources and even in glaciers [6]. Microalgae are tolerant microorganisms that can be cultured under different conditions and are grown in a wide variety of locations around the world [7]. Algal biomass can be obtained by culturing them in appropriately designed production systems. Most importantly, they can be cultivated without using valuable resources for other applications such as freshwater or arable land. Microalgae are fast-growing microorganisms that can double in less than a day, reach a high biomass productivity of over 100 t/ha (by dry weight) per year, and use sunlight as an energy source with high efficiency. For these reasons, they are considered as the basic material for the development of sustainable processes that contribute to the global bioeconomy[8].

II. ALGAE AS HUMAN FOOD

The use of microalgae as food was first started in Germany, after the First World War, in the middle of the last century, with the increase in population and the emergence of food shortages [9, 10]. Commercialization efforts that started in the 1950s gained momentum with the production of *Chlorella* sp. in the 1960s and *Arthrospira (Spirulina)* microalgae in the 1970s. In the 1980s, large-scale microalgae production facilities began to be established in Asian countries, Israel and Australia. Today, approximately 200 microalgae species are used in such studies worldwide, and the productive ones are produced on an industrial scale [11].

In addition, with the rapid decline of natural resources, the shortage of raw materials, the need for sustainable development and the transition to the global bioeconomy, microalgae have started to attract the attention of scientists and engineers in the last half century due to their many characteristics. One of these features is that these creatures are photosynthetic and can convert CO₂ and water into organic matter with the sun and produce O₂ at the same time. Moreover, annual biomass conversion efficiency of microalgae is much higher than that of plants [12]. While this rate is 3% for microalgae, it is less than 1% for higher plants. In addition, microalgae are not as adversely affected by seasonal climate changes as terrestrial plants [13, 14]. Another reason why microalgae have attracted so much attention is that they

can be grown in wastewater or outside of farmland without the use of pesticides. Thus, there is no need to compromise on the production of food crops or other products, and there is no pesticide pollution. In addition, it is another gain that they reduce atmospheric carbon dioxide and eliminate its negative environmental effects [15].

Despite difficulties such as economic feasibility and energy use, microalgae biotechnology is developing rapidly and its importance is increasing day by day [4, 9, 11, 16-18]. Today, Microalgal Biotechnology studies are gathered in four main research areas: wastewater treatment, CO₂ sequestration, biofuel production and high value-added molecule production [19, 20].

It is known that a lot of work has been done on biofuel production, a certain saturation has been reached on this subject, and the focus of current microalgae biotechnology applications has changed and shifted towards the production of high value-added molecules rather than environmental applications. This change can be associated with the high cost of microalgae production and harvesting and the low biomass production (3g/L). All these difficulties have led scientists to research and find new, higher value-added strategies for the evaluation of biomass. Recently, scientists have started to carry out studies aiming to increase the diversity and amount of primary and secondary metabolites to be obtained from microalgae, to investigate the effects of different culture conditions on this, and to reduce the production cost [21].

High value-added molecules are a very broad category that includes lipids, proteins and carbohydrates used in food and nutraceutical applications, and pigments and sterols used in cosmetics and pharmaceuticals. This wide range of applications is due to the fact that microalgae are one of the oldest life forms on earth. The fact that microalgae have evolved over billions of years and adapted to different habitats has caused them to produce enormous variation and produce such a variety of molecules. Microalgae have high nutritional value as they have the listed substances: high protein concentration containing essential amino acids, high lipid content rich in PUFAs, bioactive carbohydrates such as polysaccharides, fatty acids such as EPA (eicosapentaenoic) and DHA (docosahexaenoic), which are essential for human and animal health, and pigments such as carotenoid, chlorophyll, phycobiliprotein, which have antioxidant properties. Bioactive substances obtained from microalgae can show antioxidant, antibacterial, antiviral, antitumor, regenerative, antihypertensive, neuroprotective and immunostimulating effects [22]. These compounds are used in pharmacology, medicine, cosmetics, chemical industry, fish farming, energy industry, agriculture, feed/feed additive and functional food production [23].

The most produced microalgae species worldwide are *Spirulina*, *Chlorella*, *Dunaliella* and *Haematococcus* genus, and they are still frequently consumed in the food industry in tablet or capsule form. *Spirulina* is the most produced microalgae worldwide [24, 25]. Global production is calculated as 15000 tons per year and 10000 tons of this amount is produced in China. In addition, phycocyanin is extracted from this microalga and 200 tons of phycocyanin are produced annually worldwide [26].

In microalgae cultivation, the USA ranks first and China ranks second, followed by other countries. FAO data underestimate the true scale of world microalgae farming due to

the lack of data from major producers such as Australia, Czechia, France, Iceland, India, Israel, Italy, Japan, Malaysia, Myanmar and the United States[27].

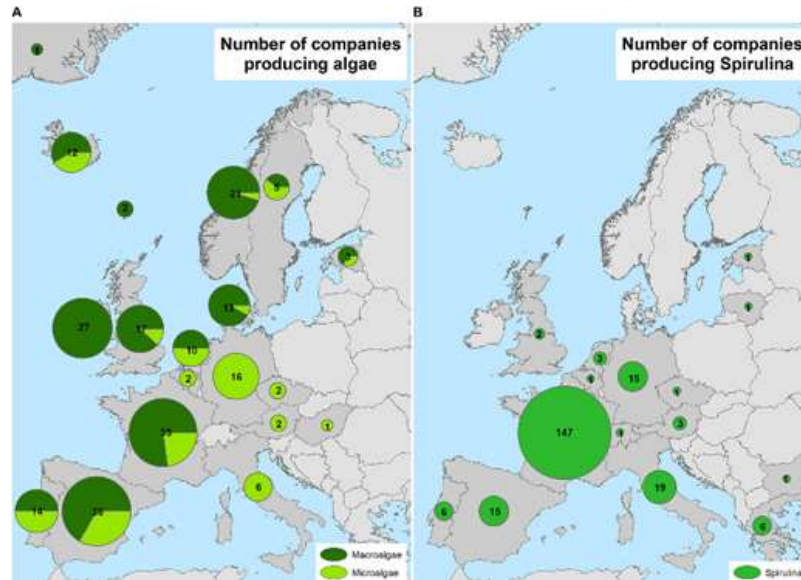


Figure 1: Algae production companies worldwide[28].

The 3 main components of agricultural products, which are food sources, are protein, carbohydrates and lipid. These products contain the most carbohydrates, while protein and lipid are less[29]. Algae attract attention as an alternative food source with high protein and lipid. They are also rich in essential amino acids and fatty acids. Because of these properties, it is already used as a food additive [30, 31].

Omega 3 fatty acids, which are vital for the development of the nervous system, circulatory system and brain and cannot be produced directly by human cells, are abundant in microalgae [32]. Salmon is often cited as a source of omega 3, but it is also transferred to salmon from algae through the food chain. For this reason, microalgae, which is the first link of the food chain, is a source of omega 3. Omega 3 can also be obtained from plant sources, but this cannot be sustainable because it requires the occupation of agricultural lands and the use of water [33, 34].

Algae have a protein production potential of 4 to 15 times more per acre than traditional crops such as wheat, maize and rice. In addition, they are very rich in essential amino acids, which are of vital importance in human nutrition [35]. These properties of algae pave the way for their use in human nutrition to improve food quality[36].

[37] summarized nutrient content of algae and highly produced traditional crops as comparatively. When Table 1 is examined carefully, spirulina and *Chlorella vulgaris* microalgae has a higher protein, carbohydrate and lipid content than other agricultural products.

Table 1: Comparison of protein, carbohydrate and lipid contents of chlorella and spirulina microalgae and traditional agricultural products.

| Nutrient (% w/dw)** | <i>Spirulina</i> sp. | <i>Chlorella</i> <i>avulgari</i> s | Soybeans,(Mature seeds,raw) | Wheat (Enriched,U nbleached) | Rice flour, (White,unenriched) | Corn flour, (yellow,finemeal,enriched) |
|---------------------|----------------------|------------------------------------|-----------------------------|------------------------------|--------------------------------|--|
| Lipid | 2.2[38] | 0[40] | 19.9[39] | 1.48[41] | 1.3[42] | 1.74[40] |
| Protein | 63[38] | 60[40] | 36.5[39] | 13.1[40] | 6.94[40] | 6.2[40] |
| Carbohydrate | 22[38] | 40[40] | 30.2[39] | 73.2[40] | 79.8[40] | 80.8[40] |

*Modified by [37]; **w/dw: weight/dry weight

Algae are not only rich in macronutrients necessary for humans, but also in vitamins, minerals and pigments. One of these pigment families is the carotenoids, which are the precursors of vitamin A in human cells. Carotenoids both act as accessory pigments in photosynthesis, increase the amount of light absorbed, and contribute to the scavenging of reactive O₂ species [43, 44]. These properties of carotenoids enable them to prevent neurodegenerative and cardiovascular diseases and to create anticancer/antioxidant effects in humans. Astaxanthin, a type of carotenoid, is the most well-known. Synthetic astaxanthin is used for coloring salmon. However, it is necessary to obtain this substance naturally, and this is achieved by using algae as a source. lutein is another carotenoid used in food dyes and colorants [45]. Lutein is a very important substance for human eye health and must be added to the human diet.

If to summarize, molecules with commercial importance that can be obtained from microalgae used in food, feed, health and cosmetics sectors, PUFAs (DHA, EPA), chlorophylls (Chlorophyll a- b), Carotenoids (β -carotene, Astaxanthin, Lutein, Lycopene, Violaxanthin), Phycobiliproteins (Phycocerythrin), Phycocyanin, Allophycocyanin, Phycocerythrocyanin), Exopolysaccharides, Protein, Vitamins, Polyphenols, Phytosterols [46].

Each of these molecules has a role in the biochemical processes of living cells, separately and together. In the absence of these, some diseases occur as mentioned above. For this reason, it should be consumed regularly and taken as a supplement in case of deficiency. In this respect, each of them has the potential to be transformed into a commercial product.

III. ALGAE AS ANIMAL FEED

Due to the increase in human population and the parallel increase in food supply, studies on innovative and sustainable sources for livestock feed and alternative protein sources within the scope of bio-based economy have started to be carried out. In this context, it has been brought to the agenda to evaluate the opportunities for the use of algae worldwide, and many projects have been and are still being carried out for this purpose with the support of the European Union [47]. Since the valuable chemicals that microalgae can produce (such as fatty acids, colorants, vitamins) have the potential to compete with the same chemicals that can be obtained from other sources, the use of microalgae for the food and feed market is becoming increasingly important.

Microalgae should be used in animal nutrition. Because:

- On a dry matter basis, microalgae contain higher levels of crude protein, carbohydrates and lipid than conventional sources (e.g., soybeans). Most algae can be used at 14% to 33% of current feed for pigs, 12% for laying chickens and 17% for broilers without adverse effects on animal growth and performance [10].
- Most microalgae have high levels of lipid and polyunsaturated fatty acids, including EPA and DHA, and contain high levels of vitamins [48].
- Several microalgae species have proven antibacterial properties. Therefore, these algae may contribute to reducing the use of antibiotics in livestock and consequently reducing bacterial resistance to these antibiotics in both humans and livestock. Some studies have also shown the antiviral properties of microalgae. Algae may contain various types of antioxidants (chlorophyll and carotenoid pigments) that have anti-inflammatory properties and can prevent degenerative diseases [49].
- Microalgae can enhance immune responses that can prevent severe disease phenotypes in case of infection. This increases farms' daily profit levels and feed conversion ratio, and animals' reproductive capacity and maintenance of external traits such as healthy skin and shiny coats. Such effects have been shown in studies in poultry, sows and piglets, sheep and lambs, and dairy cows [50].
- Addition of certain algal species to laying hens, broilers or dairy cows resulted in increased levels of polyunsaturated fatty acids in eggs, meat and milk, respectively. Veal calves fed algae-supplemented diets had reduced cholesterol levels. The carotenoid pigment in microalgae has been implicated in changes in the pigmentation of egg yolk and the color of fried chicken [51, 52].
- Beside this, the use of algae in animal feed contributes to sustainable agriculture for the following reasons.
- The agricultural land required for algae production is significantly less than the agricultural land required for the production of the same amount of protein using traditional methods. The use of too much pesticides in the feed production process with traditional methods creates serious pollution in soil and water. In addition, the use of irrigation water in agriculture causes drought and salinity, and our soils are exposed to an irreversible degradation. When the needed protein needs are met from algae, all these problems will be eliminated and sustainable agriculture will be served.
- Algae can transform the polluting nitrogen and phosphate compounds in fertilizer and waste water into valuable products by using them in their metabolism. In the case of using wastewater in algae cultivation, environmental disasters such as eutrophication are prevented and valuable algal biomass is obtained.
- Algae take CO₂ from the atmosphere and thus reduce the amount of greenhouse gases in the atmosphere.
- In the case of local microalgae production as a protein source, imports of feed products such as soy, corn can be limited, which reduces the energy and money spent on transportation, and also reduces the dependence of countries on foreign countries.
- Obtaining EPA and DHA from algae instead of oily fish prevents the extinction of endangered fish species.
- In addition to all these benefits, there are still some challenges to the high use of algae as animal feed.

- Studies aimed at improving the quality, increasing the oxidative properties and valuable components of algae under growing, harvesting, post-harvest drying techniques and stress conditions and/or through special lighting programs are insufficient.
- In order to be able to use fertilizers, digesters, wastewater or other sources in microalgae cultivation, appropriate risk analysis should be carried out to ensure the safe use of microalgae produced here in livestock feed.
- In order to increase the use of microalgae, it is necessary to increase microalgae yield and biomass productivity and to conduct applied research in different culture conditions. In real outdoor conditions, the repetition time can exceed two days, biomass productivity drops to 40 t/ha, and photosynthetic efficiency can drop to 3% [26].
- Currently, the cost price of microalgae as an energy and protein source is still too high to compete with other compound feed ingredients. Therefore, more research is needed to prove the health-promoting properties of algae as well as their positive effects on meat, milk and egg quality. Because these features significantly increase the economic value of algae.
- When the economic feasibility of this business is detailed, the comparison of production volume values with soybean oil-meal and fish oil-meal, which are widely used in feed, clearly shows this. Total soybean oil and meal production is 200 million t/year and its current price is below 0.5 €/kg. Fish oil and meal production is over 7 million tons/year, with the current price below 2 €/kg. In contrast, the current microalgae production (oil and pulp) is estimated to be around 25,000 tons (wet)/year, with a market price of 20–50 €/kg. It has been calculated that if production approaches 10,000 tons of dry biomass per year, the cost price will fall below 5 €/kg [53, 54] and further industrialization will reduce it to less than 1 €/kg [53].

Table 2. Production costs and selling prices of commercial microalgae-based products

| Products | Production cost (USD/kg) | Selling price (USD/kg) |
|----------------------|--------------------------|------------------------|
| Whole biomass | | |
| Spirulina | 3.0 | 12.0 |
| Chlorella | 6.0 | 21.0 |
| Schizochytrium | 3.0 | 6.2 |
| Pigments | | |
| β-Carotene | 140.0 | 850 |
| Astaxanthin | 600.0 | 3000 |
| Phycocyanin | 55.0 | 698 |
| Fatty acids | | |
| EPA | 44.0 | 120 |
| DHA | 44.0 | 140 |

Adapted from [55]. The data are modified for inflation.

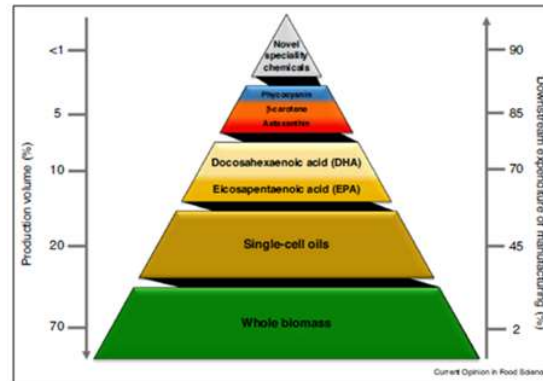


Figure 2: Production volumes and costs of microalgae-based products [55].

When Figure 1 is carefully examined, it is seen that the studies to be conducted in the field of microalgae biotechnology should shift to more specific studies - specific to the desired substance - rather than studies aiming at biomass production.

-Nonetheless, the high economic return of incorporating microalgae biomass into animal diets has already been demonstrated [56]. Because the feed mix products market has a significant impact on the animal nutrition industry. Feed mixture products have very positive effects on healthy nutrition, metabolic efficiency, effective growth and development and protection of animal health. Considering the loss of animal-product due to health problems encountered during animal production, it is certain that the production capacity that will increase with the use of microalgae-based feed additives will compensate for this.

Perspectives on the use of microalgae as food and feed are based on the diversity of biomass composition. This can be increased by strain selection or growth condition manipulation. Indeed, microalgae are able to modify their biochemical composition in response to a change in their environment. These are factors often referred to as stress parameters, such as nutrient depletion, high light intensity, extreme pH, temperature, high salinity or metal concentration. Beyond changing the macronutrient composition under stressful conditions, microalgae accumulate secondary metabolites and this is the most important factor leading to targeted bioactive compound production [46].

In the most studied microalgae species, the effects of temperature, pH, culture mixing speed [57], and culture time [58] on the amount of biomass harvested were investigated. In many studies conducted with different species, the effects of stress parameters on culture growth, biomass harvest and biochemical composition changes were investigated [59-69].

[46] published a table showing how the biochemical compositions of 36 species change depending on different culture parameters under controlled growth conditions in their review study on high value-added molecules that can be obtained from microalgae. In the same study, in a different table, data showing the change of biochemical compositions of 17 species according to stress factor (nitrogen or light) and publications of studies providing these data are given. By evaluating these tables and studies, it was determined that nitrogen and light intensity are the most effective stress parameters in the synthesis of microalgal

bioproducts. In addition, the amount of phosphorus in the culture medium affects the oil content and fatty acid composition of microalgae [70].

The amount and composition of metabolites/chemicals (protein, fat, carbohydrate, amino acid, fatty acid, vitamin, total chlorophyll and carotenoid, phenolic acids, total antioxidant substance) of biomass obtained from microalgae that have economic importance and can be converted into commercial products (powder, tablet or capsule) should be determined. In the future inspired by the current literature showing the latest state of microalgal biotechnology studies, researches should be conducted on enriching and obtaining more substances produced by microalgae. For this aim, effects of culture conditions and strain diversity can be researched. Also in order to increase the impact of the study, transcriptomic analyzes can be added that will reveal the biochemical changes occurring in the cell at the genome level and determine the metabolic pathway of the cell during the synthesis of the relevant metabolite by RNA-seq methods.

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