The Importance and Prospects of the Use of Algae in Agribusiness

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Abstract: Agribusiness could be the most promising sector for algae biomass exploitation and popularization. In this paper we summarize the scope of interests in agribusiness which can be fulfilled with algae exploitation. A high growth rate, a high ability to bind carbon dioxide and the potential to accumulate biogenic elements and light metals mean that algae can be used as a raw material for production of biofertilizers, biopesticides, feeds and feed additives. The use of the means of agricultural production based on algae can take place both in organic and conventional agriculture. The development of innovative and low-cost technologies of algae production, including the possibilities of their use in rural areas, provide a basis for changes, improvements and modifications to the existing solutions in the scope of production and use of industrial means of agricultural production. We also show that although there are quite diverse methods of production, and various micro and macro species diversified in chemical content, the economic viability of algae-based agribusiness is still in its infancy. The wide utilization of algae for food product manufacturing opens alternative ways for food acquisition, protecting both the food supply and the planet’s resources. The sustainability aspects of mass algae production implementation seem to be indisputable regarding possible benefits resulting from such technology. The versatility of algae application in food products, along with the very high nutritive and bioactive profile of this ingredient, make this resource of high importance in a low-emission economy.

Keywords: food industry; agriculture; algae biomass; feed; macroalgae; carbon dioxide sequestration

1. Introduction

Agribusiness, in material and functional terms, covers all economic activities related to the production, processing and distribution of food, as well as economic activities related to the supply of production means and services to agriculture and the agri-food industry [1–3]. In recent years in the agribusiness area, some attempts have been made towards transition to an economy based on biological and renewable resources, implementing solutions based on the ideas of bioeconomy and a closed-loop economy (circular economy) [4–6]. This is strictly related to the problems of exploitation of the environment and natural resources in food systems, including negative externalities. In order to increase food production, improve its quality and ensure food security, the use of algae seems to be an important
element in the agribusiness system, which additionally may affect the development and sustainability (economic, ecological and social) of food systems. Such an approach is also important from the perspective of the potential for productivity gains and the increased use of innovative solutions that can contribute to entrepreneurship and environmental protection.

The issues related to environmental protection in agriculture have become a subject of particular interest in recent years. The main problem is excessive pollution of soil, water and atmospheric air caused by intensive cultivation of plants and livestock production. The threats to the natural environment resulting from agricultural activity include, inter alia, ammonia and greenhouse gas emissions. Agriculture is one of the largest anthropogenic sources of greenhouse gas emissions [7,8]. In addition, the use of agrochemicals, mainly mineral fertilizers and pesticides, increases the pressure on the natural environment [9]. Excessive use of chemical means of production in agriculture may cause serious ecological problems (eutrophication, etc.). Therefore, it is necessary to undertake actions, on theoretical and practical grounds, that will limit the adverse impact of agriculture on the natural environment.

A very promising option can be both the direct and indirect use of algae biomass in agricultural production, which may significantly affect the development of low-carbon agriculture. Not only socio-economic benefits, but also many advantages for the environment and ecosystems are important in the investigated problem area [10–15], and sustainable production is one of the critical barriers in algal research [16].

The lack of a general economic overview regarding the theoretical and practical possibilities of using algae biomass as a raw material for manufacture in agribusiness is the main rationale behind this presentation. The paper compiles two of the most promising areas of use describing the options of algae exploitation for agricultural production (mainly fertilizers) and food products. In many scientific studies, a very significant potential of algae in particular areas of agribusiness is indicated (market of agricultural supply and agricultural production, food industry), but there is no comprehensive approach describing the use of algae in agribusiness as a subsystem of the national economy. Therefore, the first chapter of the paper discusses the carbon dioxide sequestration by algae, different types of algae growing systems, and the potential of algae as fertilizer and animal feed. The second chapter summarizes the state-of-art regarding the direct application of microalgae in food products as well as the perspective of macroalgae (seaweeds) consumption. Due to the need to develop sustainable production systems in agribusiness, there is a need for a broader and deeper look at this issue.

2. The Use of the Algae in Agricultural Production—Potential and Directions of Use

Algae are eukaryotic photosynthetic microorganisms characterized by a simple cell structure and a rapid growth rate [17]. Algae are a group of thalloid organisms with a high photosynthetic efficiency and with the ability to accumulate large amounts of lipids [18]. The capability of carbon dioxide sequestration by algae (Figure 1) is important from the viewpoint of the considerations made in this study.
Biological sequestration of CO₂ by algae consists of direct transformation of CO₂ into biomass. Biological sequestration by algae provides a potential to not only reduce CO₂ emissions, but also to use the biomass for energy purposes as well. It is worth emphasizing that the biomass from algae has been used in various industries, mainly in the cosmetic and pharmaceutical sectors [20,21].

Applications of algae depend on their chemical composition that varies depending on their species. Each species of algae has a different morphology and characteristics. The size of algae organisms is also differentiated—from microscopic organisms such as microalgae to macroalgae and seaweeds with a length reaching a few dozen meters [22]. The biomass of macroalgae is recovered from surface water, while microalgae are cultivated in artificial systems. Algae production systems are shown in Figure 2.

Macroalgae provide a raw material for obtaining hydrocolloids (agar-agar, alginates, carrageenan), while microalgae are used for food components, cosmetics, etc. [24,25]. Artificial enrichment of macroalgae thalli with microelements opens new possibilities for further biomass processing in various sectors of the economy, including agriculture [26]. Microalgae are also a source of biomass for energy purposes (biomethane, biodiesel, biohydrogen) [27–33]. As emphasized by Gavrilescu and Chisti [34], the cultivation of algae for energy purposes reduces the threat of global warming, because it reduces the consumption of fossil fuels and uses significant amounts of CO₂. In this context, algae have a huge potential to reduce greenhouse gas (GHG) emissions [35–37]. The possibility to use algae in the processes of wastewater treatment is important from the point of view of environmental protection [22]. A relatively new direction...
for the use of algae biomass is agriculture. The possibilities of using algae in plant and animal production are presented in Figure 3.

Figure 3. Applications of algae biomass in agricultural production.

For proper growth and development, cultivated plants require various mineral components, both macro- and micro-nutrients. Algae contain macro- and micro-elements, including nitrogen, phosphorus, potassium, sulfur, iron, copper, bromine, zinc, iodine, calcium, magnesium and manganese. These components are available in an easily assimilable form. Such features of algae predispose them to production of bio-fertilizers, plant biostimulants and agents for improving soil properties [38,39]. Mineral components as well as amino acids, vitamins, cytokinins, and auxins affect the cellular metabolism in the treated plants, which leads to improving their efficiency, growth and yield.

Another possibility of using algae in agricultural production, in terms of the means of agricultural production, is the production of feeds and feed additives [40–42]. Due to their chemical composition and content of polyunsaturated fatty acids, marine algae can provide a raw material for production of feeds and feed additives. Algae can also be widely used for feeding fish in aquaculture. In addition, as emphasized by Chojnacka [43], algae extracts have properties of biostimulators and bioregulators. Algae have many applications in various types of preparations used to protect and stimulate the growth of plants. Macroalgae of species such as Ascophyllum nodosum, Ecklonia maxima, Durvilea potatorum, Durvilea antarctica, Fucus serratus, Himanthalia elongate, Laminaria digitata, Laminaria hyperborea, Macrocystis pyrifera and Sargassum spp. are used as a raw material in preparation of the extracts used in plant health products and fertilizers [43]. As indicated by Chojnacka et al. [44], it is also possible to use the mineral components excreted in animal faeces as a nutrient for cultivation of microalgae in modern agriculture.

Some field studies have proceeded on very demanding crops, e.g., Dineshkumar et al. assessed exploitation of Chlorella vulgaris and Spirulina platensis as a biofertilizer for rice cultivation. The rice yield increased from 7%–20.9% respectively, which makes microalgae a viable “green” alternative for chemical fertilizers [45].

The use of algae as components of agricultural inputs, given their importance in terms of economic, environmental and social benefits, is an important aspect of sustainability in agribusiness. Innovations related to the increase of efficiency (productivity) in plant production, ensuring a higher level of health and welfare of farm animals, require the acceptance of farmers. This reinforces the changes in agricultural...
practices, the need to introduce changes and demonstrate a pro-innovative attitude. In the context of agriculture, this issue must take into account the specific characteristics of the sector.

The economic viability of algae production still is at the level of estimation, although different algae biomass utilization pathways have been identified and studied [46]. Cruce and Quinn performed an extensive techno-economic analysis to evaluate the suitability of biofuels and co-products from algae. They showed that for hydrothermal liquefaction, protein extraction, fractionation and novel pathways, the results were comparable to other biofuel studies, at $5.37, $4.44, $4.31 and $11.13 gge\(^{-1}\) respectively. They also showed that mixing the algal biorefinery with the treatment of wastewater surprisingly provided only minor benefits to system economics [47].

3. Algae in the Food Industry

The concept of functional food is conquering the world and inspires both science and industry to search for innovative ingredients capable of certain physiological effects to incorporate into food products. Marine waters form the environment for the existence of very different species, many of them extraordinary and rich in desired ingredients with anticancer, anti-inflammatory and antioxidant activity [48,49]. To enhance the bioactivity of food products, the exploitation of microalgae seems to be justified, as their chemical components increase the nutritional value of food products.

Microalgae have entered the food market in the form of food supplements, mainly tablets, capsules or powders and sometimes liquid suspensions or extracts. They have been immediately included in the “superfoods” category, finding their niche in the rising consciousness of consumers aware of the benefits coming from a healthy diet. Microalgae biomass is a superconcentrated source of many active ingredients among which vitamins are of high significance for bioactivity, especially A, C and E vitamin groups as well as B1, B2, B6 and B12 coupled with niacin, biotin, nicotinate and acids such as folic and pantothenic) [50]. Its nutrient composition shows especially high level of proteins with essential amino acids, hydrocolloids of the polysaccharide group, antioxidant compound such as carotenoids and chlorophylls, active enzymes, monounsaturated and polyunsaturated fatty acids (MUFAs and PUFAs) and minerals. This makes microalgae a future food that is more sustainable and with a lower carbon footprint than any other food raw material resource [48,50–52].

Not only supplements but also traditional forms of food products such as pasta, snack foods, candy bars and gums, drink mixes and beverages have been recently introduced into the market. Additionally, microalgae biomass fractionation into specific parts rich in proteins, polysaccharides or fatty acids has become an alternative way of microalgae utilization [53]. Microalgae incorporation into different food products attracts researchers’ attention due to its techno-functional and nutritional benefits (Table 1).
Table 1. Microalgae species suitable for food products incorporation and their application.

| Microalgae sp. | Product | Purpose | References |
|----------------|---------|---------|------------|
| Aporosa fusiformis | bread | Nutritional properties (proteins and mineral content) | [54] |
| Arthrospira maxima | vegetarian food gels, pasta | Techno-functional and nutritional properties (antioxidative activity, ω-3 PUFAs) | [55–59] |
| Arthrospira platensis | dairy products (fermented milk), natural and probiotic yogurt, biscuits, bread, gluten-free bread, pasta | Techno-functional and nutritional properties (protein, fiber, mineral content and antioxidative activity) | [60–67] |
| Arthrospira sp. | frozen yogurt, bread, extruded snacks | Techno-functional properties and nutritional properties (proteins content) | [68–70] |
| Chlorella vulgaris | cookies, biscuits, vegetarian food gels | Colouring agent, techno-functional and nutritional properties (antioxidative activity, ω-3 PUFAs) | [57,67,71] |
| Chlorella vulgaris green and Chlorella vulgaris orange (before and after carotenogenesis) | oil/water emulsions pasta, oil/water emulsions | Techno-functional properties, coloring and nutritional properties (antioxidative activity) | [58,72,73] |
| Chlorella sp. | yogurt, processed cheese | Techno-functional properties and nutritional properties | [74,75] |
| Dunaliella salina | pasta | Techno-functional properties and nutritional properties | [76] |
| Dunaliella sp. | vegetarian food gels, pasta | Techno-functional and nutritional properties (antioxidative activity, ω-3 PUFAs) | [57,77,76] |
| Dunaliella sp. | bread | Nutritional properties (protein content) | [79] |
| Haematococcus pluvialis | cookies, vegetarian food gels | Techno-functional and nutritional properties (antioxidative activity, ω-3 PUFAs) | [55,57,80] |
| Haematococcus pluvialis (after carotenogenesis) | oil/water emulsions | Coloring and nutritional properties (antioxidative activity) | [73] |
| Isochrysis galbana | pasta, bread, biscuits | Techno-functional properties and nutritional properties (ω-3 PUFAs) | [77,78,81] |
| Nannochloropsis gaditana | bread | Techno-functional properties | [81] |
| Oscillatoria amphibia | bread | Techno-functional properties and nutritional properties | [64] |
| Phaeodactylum tricornutum | biscuits | Techno-functional properties and nutritional properties (antioxidative activity) | [67] |
| Scenedesmus almeriensis | bread | Techno-functional properties | [81] |
| Tetraselmis suecica | biscuits, bread | Techno-functional properties and nutritional properties (antioxidative activity) | [67,81] |

Currently the number of microalgae species is estimated at up to 800,000, but still only a few are used in the food industry [82]. The wider adoption of this raw material is restricted and controlled by law. The regulatory status of algae ingredients is under the responsibility of the Food and Drug Administration (FDA) in the USA which assigns GRAS status (Generally Recognized as Safe) to a product [83], while in Europe the member state competent authority makes a first assessment of a new product, which later needs to be authorized by the European Commission (EC). If any of the member states submit any objection to the European Food Safety Authority (EFSA), it is obliged to proceed with a safety assessment [84].
Microalgae could be a very valuable added source of bulk proteins as they can significantly satisfy the need for protein, especially from the perspective of a rising population. Microalgae protein (MP) can sometimes be superior compared to the currently dominating protein sources, especially because they have quite low land requirements. One kilogram of MP requires less than 2.5 m² [85] compared to 1 kg of pork production at 47–64 m², 42–52 m² for 1 kg of chicken meat and 144–258 m² in the case of beef meat [86]. Astonishingly, some very popular plant protein sources widely promoted as meat protein alternatives have higher land requirements than MP, especially some intensively cultivated for food and feed such as soybean and pea protein [87]. Of high interest should be the possibility of non-arable land exploitation for algae cultivation, the negligible freshwater needed, and seawater adequacy for cultivation [88].

Not only microalgae but also macroalgae/seaweeds are traditionally used in many maritime countries as a source of food and for other industrial applications. The most abundant utilization of seaweeds as food is observed in Asia, particularly Japan, Korea and China, where industrial seaweed cultivation is a part of the country’s economy. In the countries of the West, the cultural heritage of food resources minimized seaweed utilization and restricted the industry related to its cultivation.

Among macroalgae, several species have just been recognized and appreciated, and some of them are cultivated in European seas. Porphyra (a red alga) is a cold-water species growing in shallow seawater. Its content of 30%–35% proteins, 40%–45% carbohydrates and a lot of vitamins makes it a very popular food ingredient. In Japan, the sea vegetable product called “amanori” is manufactured. This is one of the seaweeds most utilized for food, as almost all the human population has access to porphyra and has included it somehow in their diet. Dulse (Palmaria palmata) is another red alga usually called dulse, red dulse or sea lettuce flakes. Naturally, dulse occurs on the northern coasts of both the Atlantic and Pacific Oceans. It is known to have a high vitamin content and also a high protein content, although the proteins of dulse lack essential amino acids. Dried Palmaria palmata is served as a salty cocktail snack in the bars of Nova Scotia and Maine, and in Ireland is eaten raw or cooked [89].

Laminaria (a brown alga), also known as kelp, belongs to the brown algae family whose species contain about 2% fat with 10% of protein and a significant amount of essential mineral constituents such as iodine, potassium, magnesium, calcium and iron. The popularity of macroalgae exploitation is reflected in a huge cultivation industry, mainly located in the East. Laminaria species are commonly cultivated and grown on ropes, in cylinders and on seashore stones. The market demand for this brown alga is huge as it constitutes the main ingredients of food products known as “kombu” or “konbu”, which are extensively used in Japanese cuisines as one of the basic ingredients necessary to make dashi, a soup stock. The other brown alga is the genus of Alaria, which comprises approximately 17 species, which are commonly eaten dried in Western Europe, South America, China, Korea and Japan. The Japanese food product “sarumen” is based on the Alaria genus seaweeds, and Alaria esculenta particularly provides both protein of excellent quality and iodine. The kelp seaweed most often used as food is called cochayuyo in Chilean and belongs to the Durvillaea antarctica species (a robust bull kelp species). Durvillaea dominates the southern New Zealand and Chilean shores. It is very popular in Chilean cuisine as the stem (known as hulte) is used for different recipes, such as salads and stews [89].

Another genus of microalgae is Monostroma (a green alga), and along with the Ulva genus it is commercially cultivated in bay areas of Taiwan, Korea and Japan. High levels of calcium, magnesium and lithium along with vitamins and amino acids such as methionine make Monostroma a very nutritious raw material. It is a leafy plant of one-cell thick form. Commonly it is processed into sheets and dried and then boiled with the addition of sugar, soy sauce and other ingredients to prepare “nori-jam”. The next popular green macroalgae from the Ulva genus is well known as sea lettuce. Ulva is not cultivated but harvested and mixed with Monostroma and Enteromorpha sp. to create a food product called “aonori”, which is used as a seasoning for everyday warm dishes like rice, soups and salads. Ulva is especially rich in protein and iron and is also known in Europe, especially in Scotland where Ulva lactuca was utilized for salads and
soups. Bay and river mountains of Japan are the perfect environment for the cultivation of Enteromorpha genus, a previously independent genus and now classified as Ulva and called “green nori”. This green alga is also known in Europe and North America and is quite well exploited after drying as a garnish or even slightly toasted for flavor improvement. To the group of green alga also belongs the species of *Caulerpa racemosa* which is also known as sea grapes. The shallow sea areas are the habitat of this species and it is consumed mainly in salads in the Australasia region, especially Thailand, Fiji, the Philippines and Japan. This seaweed is very rich in proteins, fiber, minerals such as calcium and magnesium, and vitamins such as folic acid, ascorbic acid, vitamin A and vitamin B1 [89].

The last species, although is not strictly from the plant kingdom, but presently classified as bacteria, is *Nostoc commune*, commonly called blue-green algae and belonging to the cyanobacteria family. It forms colonies built of filaments in a gelatinous sheath. *Nostoc* can be found in soil, on moist rocks, at the bottom of lakes and springs rather than in marine habitats. Rich in protein and vitamins, especially ascorbic acid, *Nostoc* communes are cultivated and consumed as a foodstuff, usually in the form of salad in the Philippines, Indonesia, Japan and China [89].

Microalgae are slowly starting to be perceived as a future food source. Rich in protein, fat and fiber, microalgae are a superior raw material for manufacturing novel food products. Torres-Tiji et al. discussed the future prospects of microalgae in the food market, showing that the value of the global market is very difficult to estimate due to the very early stage and wide diversity of sold products [90]. Wells et al. [91] tried to assess the global market for the most popular algae ingredients—carrageenans and alginates—returning the value of 6.7 billion USD. However, for application in food products there are still many areas to improve starting with the production process, media composition, growth systems, genotype and product yield.

4. Summary

The increasing number of studies evaluating the importance of algae for the ecosystem and the low-carbon economy confirm the potential of these organisms to be effectively incorporated into the global economy. This applies both to the possibility of using algae biomass for energy purposes and for the production of algae-based food, pharmaceutical and cosmetic products. Not so obvious is exploitation of algae cultivation and chemical content as a fertilizer replacement towards the development of low-carbon agriculture. Algae are a rich source of many elements, and thus they can be used as substrates for the production of fertilizers and feeds as well as a substrate for production of crop protection agents.

The wide spread of algae-based initiatives requires greater effort from scholars and policy makers. Cultivation of algae and commercial production of preparations from algae are at the initial stage of development. However, there is a very large potential in the scope of demand for the products made from algae. The industry is eager to exploit every economically viable business, but before that occurs the efficiency of production, level of algae fractionation and product acceptance need to be established. Dynamic development of organic farming, growing awareness of farmers concerning environmental protection, changes in tastes and preferences of food consumers in the pro-ecological direction are some factors that may affect the increase in demand for biomass from algae in agriculture. In addition, the development of algae cultivation in rural areas (in open and closed systems) may be an important aspect of sustainable and multifunctional development of agriculture. The development of the cultivation of algae and their use in the agricultural economy in terms of its low-carbon development can be considered in two dimensions: socio-economic and spatial. An increase in the use of the biomass from algae for agricultural purposes requires cooperation and joint actions of biotechnological companies, agricultural holdings as well as agricultural institutions and agencies. The institutional support for the development and commercialization of the means of agricultural production manufactured on the basis
of algae, including agricultural policy programs, is important. Research and scientific work in the area of optimal organizational models (mainly logistic ones) is required to ensure a stable supply of algae biomass, taking into account the impact of the supply chain on the natural environment. Challenges in the investigated area also concern the changes in agricultural practice—replacement of chemicals by biotechnological products.

The production of bioproducts based on algae is an important direction of agribusiness development. Current achievements in biotechnology make it possible to use them not only as a means of agricultural production but also in the production of food products. The pro-health properties of algae, while maintaining the principles of sustainable development and ecology in the process of their growth and development, promise great prospects for the future (use of algae on an industrial scale in the food industry).

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