Int. J. of Environmental Pollution & Environmental Modelling, Vol. 2(2): 90-104 (2019)
(Review Article)

Commercial Bio- products from Algal Biomass

Essam HobAllah[1], Mohamed Saber[1], Alaa Zaghloul[2*]

[1] Department of Agricultural Microbiology, National Research Centre, Dokki, Cairo, Egypt
[2] Soils and Water Use Department, National Research Centre, Dokki, Cairo, Egypt

E-Mail: *alaazaghloul2008@gmail.com*

Abstract: Most algae are fundamentally autotrophic (obtaining all their materials from inorganic sources) and photosynthetic generating complex carbon compounds from carbon dioxide and light energy. Some algae have become secondarily heterotrophic, taking up complex organic molecules by organotrophy or heterotrophy, but still retaining fundamental genetic affinities with their photosynthetic relatives. They organisms included both prokaryotes (cells lacking a membrane bound nucleus) and eukaryotes (cells with a nucleus plus typical membrane-bound organelles). They are abundantly found in environmental extremes of temperature, pH, salt concentration, and radiation. The cultivation of algae can make an important contribution to the transition to a more sustainable society or bio based economy. Algae are not only suitable for environmentally friendly production of many commodities, but also for the use of waste streams. They grow excellent on e.g. carbon dioxide from flue gases, residual water of agro-industrial companies and even diluted digestate from manure. In return they produce valuable raw materials. Algae recycle nutrients that thus remain available in the nutrient cycle, instead of being wasted and pollute the water. The algal cell contains many useful substances and microalgae are cultivated increasingly for the production of valuable raw materials such as oil, proteins, starch, agar, carrageenan, Alginate, pigments (e.g., beta-carotene) and different pharmaceutical products so that the commercial applications of these materials are numerous.
Keywords: *Algal nutrition, culturing, Photo bioreactor, biomass, harvesting, bio- products*

INTRODUCTION

The word 'algae' (singular alga) originates from the Latin word for seaweed and is now applied to a broad assemblage of organisms that can be defined both in terms of morphology and general physiology [1]. They are oxygenic phototrophic simple organisms, without differentiation into roots, stems and leaves and their sexual organs are not enclosed within protective coverings. In terms of physiology, they are fundamentally autotrophic (obtaining all their materials from inorganic sources) and photosynthetic generating complex carbon compounds from carbon dioxide and light energy [2]. Some algae have become secondarily heterotrophic, taking up complex organic molecules by organotrophy or heterotrophy, but still retaining fundamental genetic affinities with their photosynthetic relatives. The term algae is not strictly a taxonomic term but is used as an inclusive label for a number of different phyla that fit the broad description noted above. These organisms include (Table 1) both prokaryotes (cells lacking a membrane bound nucleus) and eukaryotes (cells with a nucleus plus typical membrane-bound organelles). They are abundantly found in environmental extremes of temperature, pH, salt concentration, and radiation. These extremophilic phototrophs include both prokaryotes (cyanobacteria) and eukaryotes (different types of algae) [3].

The cultivation of algae can make an important contribution to the transition to a more sustainable society or bio based economy. Algae are not only suitable for environmentally friendly production of many commodities, but also for the use of waste streams. They grow excellent on e.g. carbon dioxide from flue gases, residual water of agro-industrial companies and even diluted digestate from manure. In return they produce valuable raw materials. Algae recycle nutrients that thus remain available in the nutrient cycle, instead of being wasted and pollute the water. The algal cell contains many useful substances and microalgae are cultivated increasingly for the production of valuable raw materials. For example, it is possible to produce oil, proteins, starch, agar, carrageenan, Alginate**,** pigments (e.g., beta-carotene) and different pharmaceutical products. Commercial applications of these materials are numerous, ranging from biodiesel and bioplastics to colorants and hamburgers [4, 5].

*Corresponding E-mail: alaazaghloul2008@gmail.com

OCCURRENCE AND DISTRIBUTION OF ALGAE

Algae could be aquatic or subaerial, when they are exposed to the atmosphere rather than being submerged in water. Aquatic algae are found almost anywhere from freshwater spring to salt lakes, with tolerance for a broad range of pH, temperature, turbidity, O_2 and CO_2 concentration (Table 2). They might be planktonic, like most unicellular species, living suspended throughout lighted regions of all water bodies including under ice in polar areas. They could also be benthic, attached to the bottom or living within sediments or limited to shallow areas because of the rapid attenuation of light with depth. Benthic algae can grow attached to stones (epilithic), on mud or sand (epipelic), on other algae or plants (epiphytic), or on animals (epizoic). A considerable number of sub aerial algae have adapted to life on land. They might occur in surprising places such as tree trunks, animal fur, snow banks, hot springs or even embedded within desert rocks. Algae also form mutually beneficial partnership with other organisms. They live with fungi to form lichens or inside the cells of reef-building corals, in both cases providing oxygen and complex nutrients to their partner and in return receiving protection and simple nutrients. This arrangement enables both partners to survive in conditions that they could not endure alone [6,7].

PRODUCTION OF ALGAL BIOMASS

Definition of Algal Biomass

At the time being, macro- and micro-algae are currently mainly used for food, in animal feed, in feed for aquaculture and as bio-fertilizer. The algae biomass is defined as isolated and dried growth yielded from aqueous media which the selected alga grown in. Biomass from micro-algae is dried and marketed in the human health food market as powder or pressed in the form of tablets. The most frequently used species of micro-algal in of biomass for human food belong to the groups of *Spirulina*, *Chlorella*, *Dunaliella*, *Nostoc* and *Aphanizomenon*. For example about 3500 tons of *Spirulina* biomass was produced worldwide in 1999 [8].

Nutrition

Most algal groups are considered photoautotrophs that are, depending entirely upon their photosynthetic apparatus for their metabolic necessities using sunlight as the source of energy, and CO_2 as the carbon source to produce carbohydrates and ATP. Most algal divisions include colorless heterotrophic species that could obtain organic carbon from the external environment either by taking up dissolved substances (osmotrophy) or by engulfing bacteria and other cells as particulate prey (phagotrophy). However, it is widely accepted that algae use a complex spectrum of nutritional strategies, combining photoautotrophy and heterotrophy, which is referred to as mixotrophy. Some mixotrophs are mainly photosynthetic and only occasionally use an organic energy source [9].

Algal culturing parameters

Any culture has three distinct components: (1) a culture medium contained in a suitable vessel; (2) algal cells growing in the medium; (3) air, to allow exchange of carbon dioxide between medium and atmosphere. For most entirely autotrophic algae, their entire growth needs are restricted to light, CO_2, water, nutrients, and trace elements. By means of photosynthesis the alga will be able to synthesize all the biochemical compounds necessary for their growth. Only a minority of algae is, however, entirely autotrophic; many are unable to synthesize certain biochemical compounds (certain vitamins, e.g.) and requires these compounds to be present in the medium. The most important parameters regulating algal growth are nutrient quantity and quality, light, pH, turbulence, salinity, and temperature. When choosing a culture medium, the natural habitat of the species in question should be considered in order to determine its environmental requirements [10].

Table 1. Classification scheme of the different algal groups

Kingdom	Division	Class
Prokaryota Eubacteria	Cyanophyta Prochlorophyta	Cyanophyceae Prochlorophyceae
Eukaryota	Glaucophyta	Glaucophyceae
	Rhodophyta	Bangiophyceae Florideophyceae
	Heterokontophyta	Chrysophyceae Xanthophyceae Eustigmatophyceae Bacillariophyceae Raphidophyceae Dictyochophyceae Phaeophyceae
	Haptophyta	Haptophyceae
	Cryptophyta	Cryptophyceae
	Dinophyta	Dinophyceae
	Euglenophyta	Euglenophyceae
	Chlorarachniophyta	Chlorarachniophyceae
	Chlorophyta	Prasinophyceae Chlorophyceae Ulvophyceae Cladophorophyceae Bryopsidophyceae Zygnematophyceae Trentepohliophyceae Klebsormidiophyceæ Charophyceae Dasycladophyceae

Source: Barsanti and Gualtieri [11].

Table 2. Different types of habitats colonized by varied algal divisions

Division	Common Name	Habitat			
		Marine	Freshwater	Terrestrial	Symbiotic
Cyanophyta	Blue-green algae	Yes	Yes	Yes	Yes
Prochlorophyta	n.a.	Yes	n.d.	n.d.	Yes
Glaucophyta	n.a.	n.d.	Yes	Yes	Yes
Rhodophyta	Red algae	Yes	Yes	Yes	Yes
Heterokontophyta	Golden algae Yellow-green algae Diatoms Brown algae	Yes	Yes	Yes	Yes
Haptophyta	Coccolithophorids	Yes	Yes	Yes	Yes
Cryptophyta	Cryptomonads	Yes	Yes	n.d.	Yes
Chlorarachniophyta	n.a.	Yes	n.d.	n.d.	Yes
Dinophyta	Dinoflagellates	Yes	Yes	n.d.	Yes
Euglenophyta	Euglenoids	Yes	Yes	Yes	Yes
Chlorophyta	Green algae	Yes	Yes	Yes	Yes

Note: n.a., not available; n.d., not detected.

Source: Carlsson *et al.* [12].

Cultivation and production systems for algal biomass

It is important to understand the basics of algae cultivation systems. As far as some algal growing systems use more energy in lighting than what is gained as algal energy feedstock, hence only systems using natural light are considered in this document. Seaweed has historically been harvested from natural populations or collected after washing up on shore. To a much lesser extent, a few microalgae had also been harvested from natural lakes by indigenous populations. The main cultivation options are described in detail in [14]. They mentioned also those algae cultivation systems are classified to 3 main systems that included closed cultivation system (such as Photobioreactor unit), open cultivation systems (Open pond systems) and Sea-based cultivation systems.

a) Closed cultivation systems (Photobioreactors) for algal biomass

Photobioreactors are different types of tanks or closed systems in which algae are cultivated. Water, necessary nutrients and CO_2 are provided in a controlled way, while oxygen has to be removed. Algae receive sunlight either directly through the transparent container walls or via light fibers or tubes that channel it from sunlight collectors (Figure 1). Instead of light and photosynthesis, heterotrophic algae are relying on utilizable carbon sources in the medium for their carbon and energy generation [12].

b) Open cultivation systems (Open pond systems) for algal biomass

Open pond systems are shallow ponds in which algae are cultivated. Nutrients are provided through runoff water from nearby land areas or by channeling the water from sewagewater/freshwater treatment plants. The water is typically kept in motion by paddle wheels or rotating structures (Figure 2), and some mixing might be accomplished by appropriately designed guides [13].

Figure 1. Closed cultivating system units for algal biomass production

Figure 2. Open cultivation system unit for algal biomass production

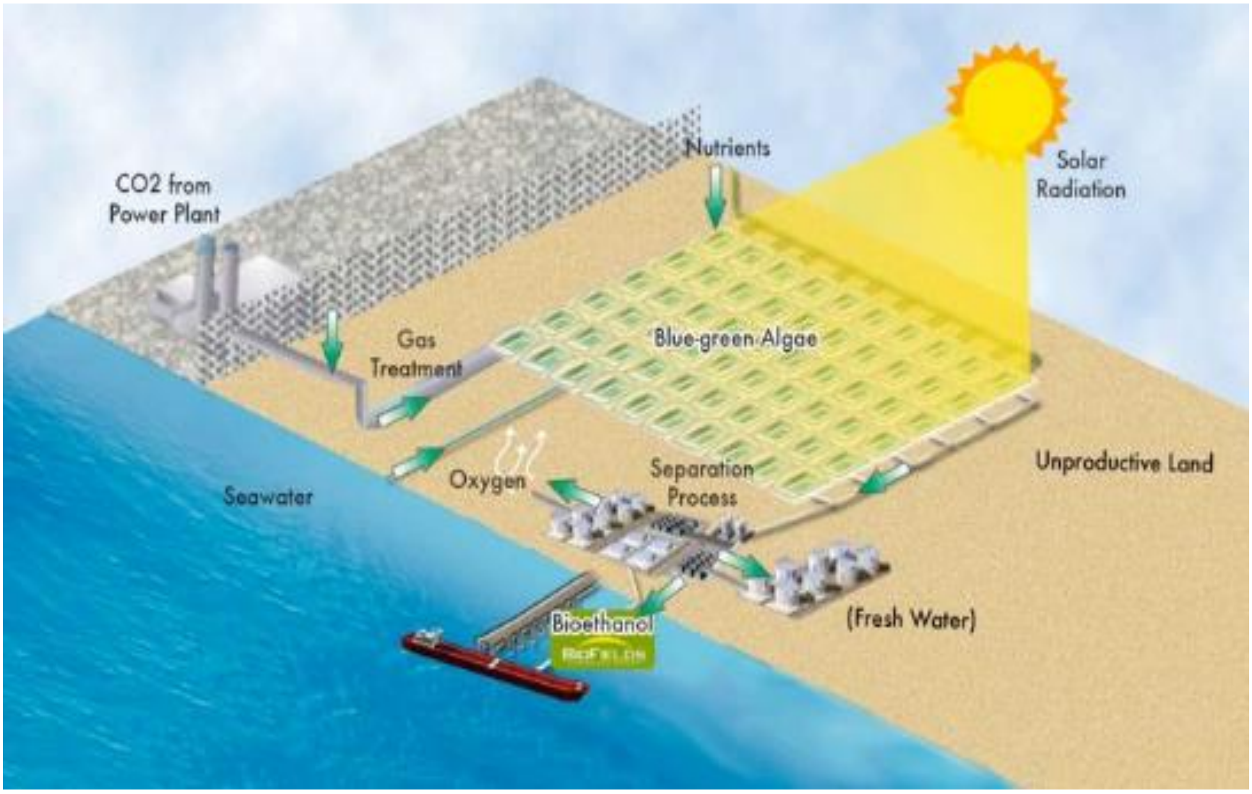


Figure 3. Sea-based cultivation systems for algae biomass

c) Sea-based cultivation systems for algal biomass

Whereas the previously described cultivation systems are almost exclusively used for microalgae, algae cultivation in the sea is the domain of seaweed (Figure 3). To make an impact as bioenergy feedstock, seaweed should be produced in floating cultivation systems spanning vast areas. Most seaweed requires a substrate to hook on; which in practice means that the cultivation system must contain a network of ropes. The amount of construction material could be drastically reduced when free-floating seaweed (like some *Sargassum* species) is cultivated as just a structure to contain the colony would then be needed [14].

Comments on the different production systems

The high capital cost associated with producing micro-algae in closed culture systems is the main challenge for commercialization of such systems. Open systems, however, do not require those high expenses associated with sterilization of axenic algal cultures. But this might lead to an appreciable risk of contamination of the culture by bacteria or other unwanted microorganisms. A common strategy therefore to achieve monocultures in an open pond system is to keep them at extreme culture conditions such as high salinity, nutrition or alkalinity. Selection of a suitable production system clearly depends on the purpose of the production facility. For example, closed bioreactors would not be suitable for wastewater treatment, because the costs for treating wastewater in this system will be too high in relation to the low value added during the production process. On the other hand, high quality/value products that are produced only in small amounts might require production in bioreactors [10].

Algal biomass harvesting

Conventional processes used to harvest micro-algae include their concentration through centrifugation (Figure 4), foam fractionation, flocculation, membrane filtration and ultrasonic separation. Harvesting costs might contribute to 20 – 30% to the total cost of algal biomass. The micro-algae are typically small with a diameter of 3 – 30 μm, and the culture broths might be quite dilute at less than 0.5 g l-1, thus, large volumes must be handled. The harvesting method depends on the species, cell density, and often also on the culture conditions [15].

Figure 4. Centrifuge used for separating algae from growing aqueous medium

COMMERCIAL BIO- PRODUCTS FROM ALGAL BIOMASS

Commercial bio- products from algal biomass and their sources are previously given in Table 4.

Algae-based bioenergy products

In recent years, biofuel production from algae has attracted the most attention among other possible products. This could be explained by the global concerns over depleting fossil fuel reserves and climate change. Furthermore, increasing energy access and energy security are seen as key actions for reducing poverty thus contributing to the Millennium Development Goals. Access to modern energy services such as electricity or liquid fuels is a basic requirement to improve living standards. An overview of algae- to- energy options is illustrated in Figure 5 [16].

Biodiesel

Biodiesel production from algal oils has received most attention since algae might contain potentially over 80% w/w total lipids, (while rapeseed plants, for instance, contain about 6% lipids). Under normal growth conditions the lipid concentration is lower (<40%) and high oil content is always associated with very low yields. The various lipids production could be stimulated under stress conditions, e.g. insufficient nitrogen availability. Under such conditions, biomass production is not optimal though, reducing the non-lipid part of the biomass that could be further used as a source for co-products. Most algal species cultivated commercially in open systems (i.e., *Chlorella*, *Spirulina*, and *Dunaliella*) for the purpose of biofuels production, are grown in highly selective, open air environments that remain relatively free of contamination by other algae and protozoa (Figure 6). Figure 7 showed a car powered by algae biofuel prove that algal biofuel started to be used instead of petroleum derivatives [12].

Hydrocarbons

One genus of algae, *Botryococcus*, does not produce the above-mentioned lipids, but produce longer chain hydrocarbons, that are not suitable for biodiesel production. Instead, they could be converted in a process similar to the production of conventional fuels from fossil oil. *Botryococcus* is a freshwater species but could also be grown in saline to produce certain carotenoids [17].

Bio-ethanol

Ethanol is commonly produced from starch-containing feedstocks; some algae had been reported to contain over 50% of starch. Algal cell walls consist of polysaccharides which could be used as a feedstock in a process similar to cellulosic ethanol production, with the added advantage that algae rarely contain lignin and their polysaccharides, are generally more easily broken down than woody biomass [18].

Hydrogen

Some algae could be manipulated into producing hydrogen gas. Currently the yield of this process is low and since energy is lost by the cells to form hydrogen, not much biomass is produced and therefore there is little potential for co-production [12].

Bioelectricity

Algal biomass can also be co-combusted in a power plant. For this, the biomass needs to be dried, to be able for combusting. This process is thus only interesting if the biomass is required to be dried in order to extract a certain co-product as a first step before being used as a biofuel [13].

Algae-based non-energy options

The number of products that could be made from algae is virtually unlimited, due to the large variety of species (possibly in the millions) whose composition could be influenced by changing the cultivation conditions. The bulk of commercial products from algae are derived from seaweed, produced for food, agar and alginates and partially harvested from natural populations, rather than cultivated. Commercial products from microalgae are largely limited to a few easily cultured species with proven market demand and market value, often as health food or feed in aquaculture. The total seaweed production in 2007 reached 16 million tons fresh weight [14]. Depending on the microalgae species, many compounds could be extracted with several applications for many industrial sectors such as cosmetics, pharmaceuticals, nutrition and food additives, aquaculture, and pollution prevention, oil, fats, polyunsaturated fatty acids, natural dyes, pigments, antioxidants, sugar, high-value bioactive compounds, and other fine chemicals and biomass [19].

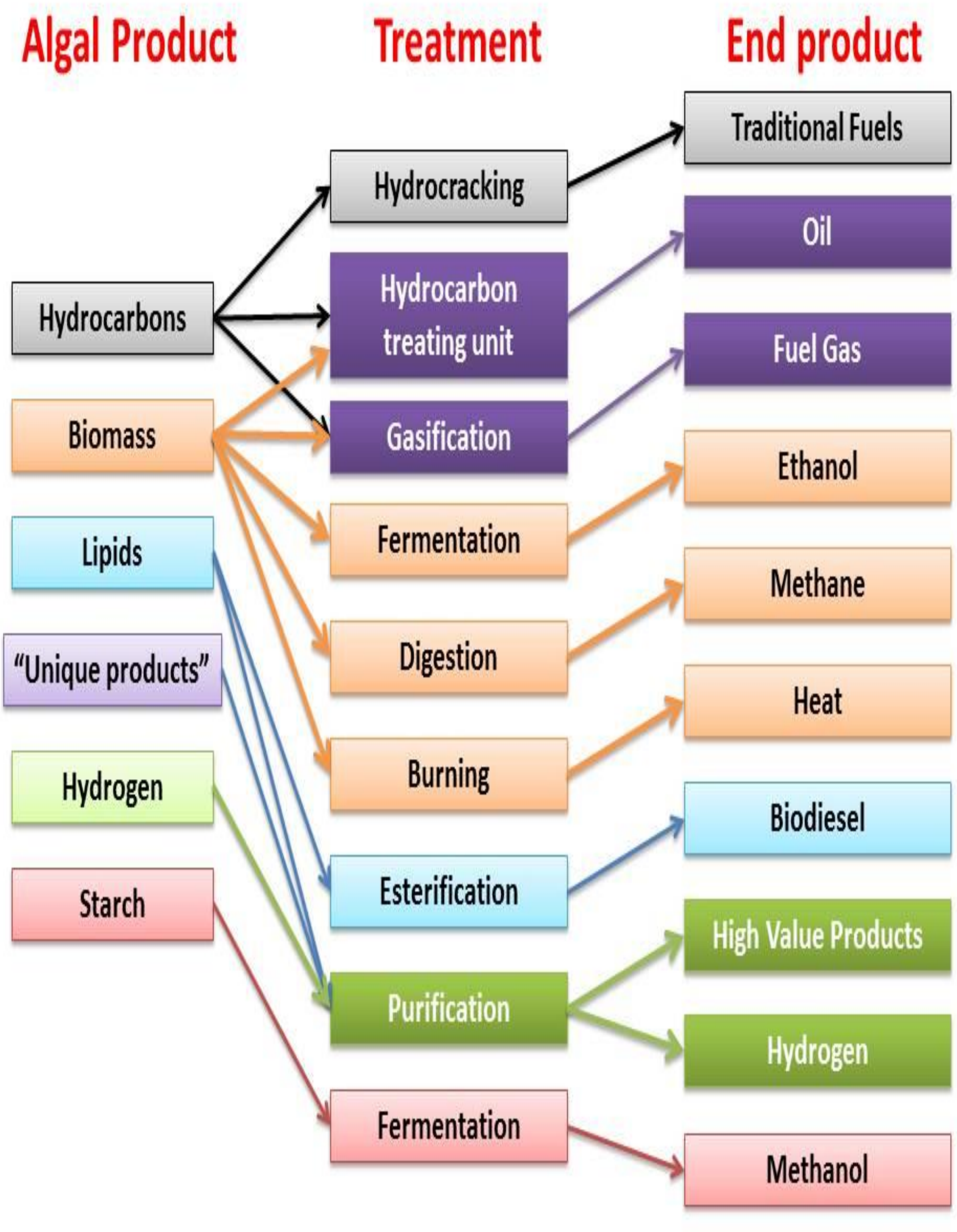
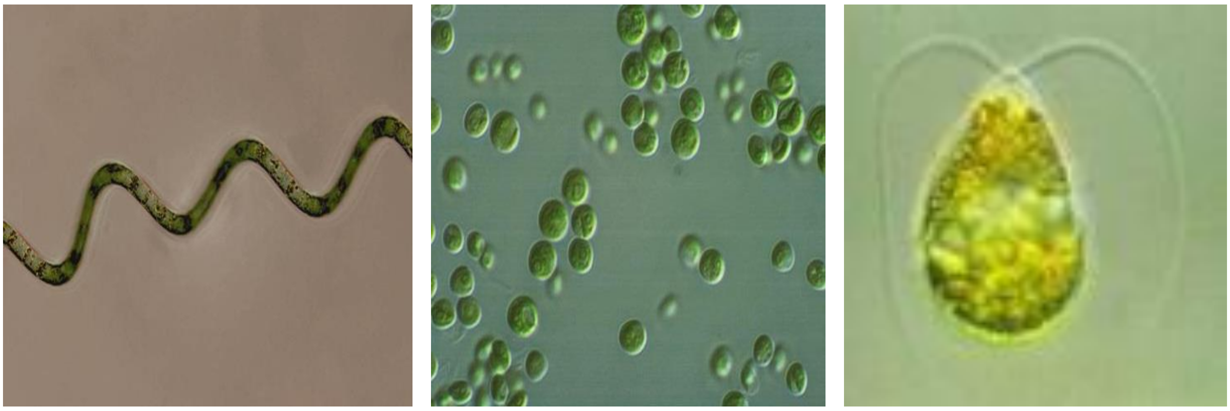


Figure 5. Overview of algae- to- energy options



Spirulina platensis ***Chlorella vulgaris*** ***Dunaliella salina***

Figure 6. Different algae used in biodiesel production

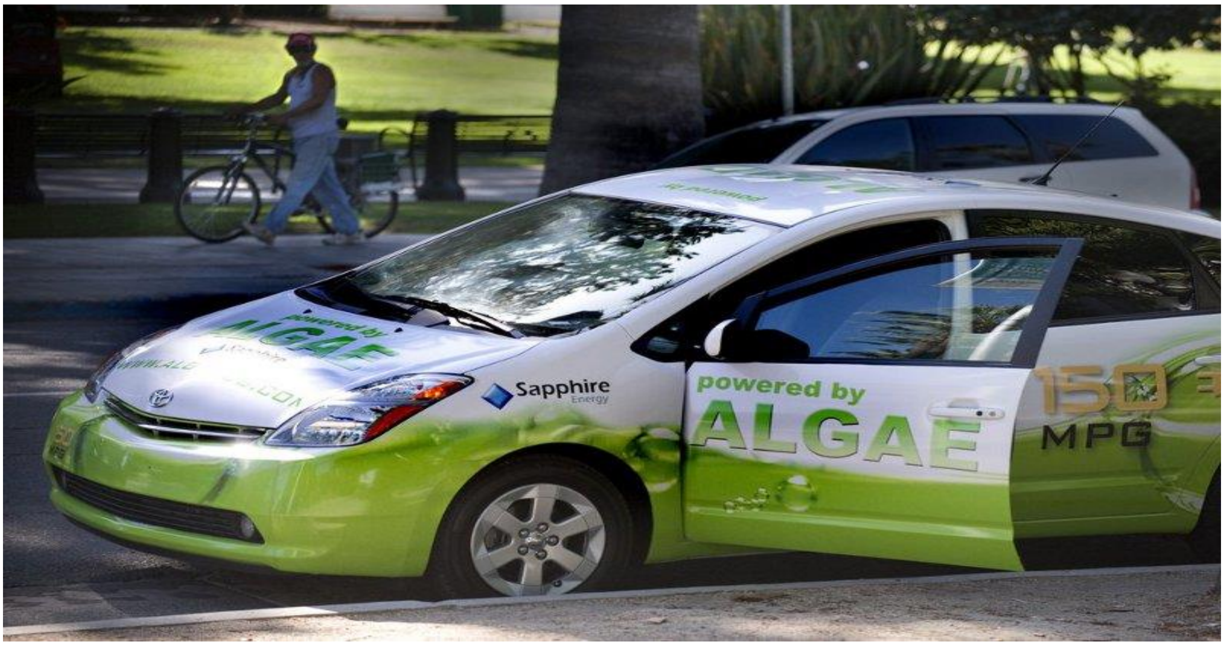


Figure 7. A car powered by algae biofuel

Algae-based products for human consumption

Algae use as food had been cited in Chinese literature as early as 2500 years ago. Several parts of Asia are well known for consuming algae (mostly seaweed) directly and some indigenous people in Africa, South America and Mexico consume small quantities of naturally occurring algae mostly because of the vitamins and nutrients they provide. Microalgae for human nutrition are nowadays marketed in different forms such as tablets, capsules and liquids. They could also be incorporated into pastas, snack foods, candy bars or gums, and beverages, noodles, wine, beverages, breakfast cereals, nutrition bars, cookies [20]. Table 3 shows the commercially produced microalgae; amounts, locations, applications and market value in2004 [20].

Staple food

Most algae cannot be used directly as a human food because the cell walls are not digestible. However, mechanical solutions, strain selection or bioengineering could overcome this problem. Digestible cell walls would potentially create the tipping point that enables algae to serve the world as food. Best known for large scale consumption are the selected species of seaweed that are eaten in Asia. The cultivation and harvesting of this seaweed is a labor intensive process. The seaweed is dried and consumed completely, leaving no option for co-production. Proteins are of major importance in human nutrition and their lack is one of the biggest factors in malnutrition. Some algae contain up to 60%

protein. A well-known alga that is currently cultivated for its protein content is the cyanobacterium species *Arthrospira*, better known as *Spirulina*. Spirulina is reported to contain not only around 60% raw protein, but also vitamins, minerals and many biologically active substances [21].

Pharmaceuticals and other bioactive algal products

In addition to food, algae provide a wide variety of medicines, vitamins, vaccines, nutraceuticals and other nutrients that might be unavailable or too expensive to produce using plants or animals. Many of the algal applications in this section are highly technical or scientific [21]. As an example, in *Chlorella* species, the most important compound from a medical point of view is β- 1, 3-glucan, an active immunostimulator, a free radical scavenger and a blood lipid reducer. Efficacy of this compound against gastric ulcers, wounds and constipation, preventive action against atherosclerosis and hypercholesterolemia, and antitumor action had also been reported. Microalgae also represent a valuable source of almost all essential vitamins (e.g., A, B_1, B_2, B_6, B_{12}, C, E, nicotinate, biotin, folic acid and pantothenic acid). Furthermore, sulfated polysaccharides of microalgae could be used in anti-adhesive therapies against bacterial infections both in cold- and warm-blooded animals [20].

Table 3. Commercially produced microalgae; amounts, locations, applications and market value (2004).

Microalga	Annual production	Producer country	Application and product	Price
Spirulina	3000 tons dry weight	China, India, USA, Myianmar, Japan	Human nutrition Animal nutrition Cosmetics	36 €/kg
			Phycobiliproteins	11 €/mg
Chlorella	2000 tons dry weight	Taiwan, Germany, Japan	Human nutrition Cosmetics	36 €/kg
			Aquaculture	50 €/L
Dunaliella salina	1200 tons dry weight	Australia, Israel, USA, Japan	Human nutrition Cosmetics	
			β-carotene	215-2150 €/kg
Aphanizomenon flos-aquae	500 tons dry weight	USA	Human nutrition	
Haematococcus pluvialis	300 tons dry weight	USA, India, Israel	Aquaculture Astaxanthin	50 €/L 7150 €/kg
Crypthecodinium cohnii	240 tons DHA oil	USA	DHA* oil	43 €/g
Shizochytrium	10 tons DHA* oil	USA	DHA* oil	43 €/g

*DHA (Docosahexaenoic acid) is an omega-3 fatty acid that is a primary structural component of the human brain cerebral cortex, sperm, testicles and retina [14].

Polyunsaturated fatty acids (PUFAs)

PUFAs are important nutrients that must be supplied by external sources as they cannot be produced by the organism itself. Well-known PUFAs include ω−3 fatty acids the most well-known source of PUFAs is fish oil. However, fish do not produce PUFAs but accumulate them by eating algae (or other algae-eating organisms). Algae are the true source of these essential nutrients. PUFA production from algae had been developed only in the last decade with advantages of lacking unpleasant fish odor, reduced risk of chemical contamination and better purification potential [22]. PUFAs are known to play an important role in reducing cardiovascular diseases, obesity, in cellular and tissue metabolism, including the regulation of membrane's fluidity, electron and oxygen transport, as well as thermal adaptation ability. Algae groups that contain PUFAs include diatoms, *crysophytes, cryptophytes* and *dinoflagellates* [21].

Ingredients for processed foods

The most economically-valuable algae products are the macroalgal polysaccharides, like agar, alginates and carrageenans, especially due to their rheological gelling or thickening properties. An increase in research and development activities on microalgae, transgenic microalgae, protoplast fusion, or macroalgal cell cultures as biotechnological sources had been observed in the last years [22]. As previously mentioned, many pigments from algae could also be used as natural food colorants [23].

a) Agar

Agar is made from seaweed and is used in a wide range of applications: in food products (such as frozen foods, bakery icings, meringues, dessert gels, candies and fruit juices), industry uses (like paper sizing/coating, adhesives, textile printing/dyeing, castings, impressions), in biological culture media, in molecular biology (more specifically agarose, used for separation methods) and in the medical/pharmaceutical field (to produce bulking agents, laxatives, suppositories, capsules, tablets and anticoagulants). When used in the EU, it is listed in the ingredients as E406 [12].

b) Carrageenan

Carrageenan is a water soluble group of polysaccharides that are more widely used than agar as emulsifiers and stabilizers in numerous (especially milk-based) foods. κ- and ι- carrageenans are especially used in chocolate milk, ice cream, evaporated milk, puddings, jellies, jams, salad dressings, dessert gels, meat products and pet foods, due to their thickening and suspension properties. Several potential pharmaceutical uses of carrageenans (like antitumor, antiviral, anticoagulant and immunomodulation activities) have also been explored. When used in the EU, it is listed in the ingredients as E407 [12].

c) Alginate

Alginate (or alginic acid) is produced by brown seaweed and is used in the textile industry for sizing cotton yarn. Its gelling capabilities make it of considerable technological importance. It is widely used in the food and pharmaceutical industries due to its chelating ability and its capability to form a highly viscous solution When used in the EU, it is listed in the ingredients as E400 to E405, depending on the form of alginate [22].

Pigments

Microalgae contain a multitude of pigments associated with light incidence. Besides chlorophyll (the primary photosynthetic compound) the most relevant are phycobiliproteins (they improve the efficiency of light energy utilization) and carotenoids (they protect them against solar radiation and related effects). Carotenoids from microalgae have already many applications in the market: β-Carotene from *Dunaliella* in health food as a vitamin A precursor; Lutein, zeaxanthin and canthaxanthin for chicken skin coloration, or for pharmaceutical purposes and Astaxanthin from *Haematococcus* in aquaculture for providing the natural red colour of certain fish like salmon [22]. The antioxidant functionality of carotenoids is of major importance for human consumption. Anti-oxidants function as free radical scavengers, which gives them an anti-cancer effect [24].

Cosmetics

The use of some microalgal species, especially *Arthrospira* and *Chlorella*, is well established in the skin care market and some cosmeticians had even invested in their own microalgal production system (LVMH, Paris, France and Daniel Jouvance, Carnac, France). Their extracts are found in e.g. anti-aging cream, refreshing or regenerating care products, emollient, exert a skin tightening effect, prevent stria formation, and stimulate collagen synthesis in skin and as an anti-irritant in peelers and also in sun protection and hair care products [21].

Algae-based products for animal consumption

Algae for livestock consumption

The use of micro-algae as animal feed is relatively recent and predominantly aimed at poultry, mainly because it improves the color of the skin, shanks and egg yolks. Multiple nutritional and toxicological evaluations demonstrated the suitability of algae biomass as a valuable feed supplement or substitute for conventional protein sources (soybean meal, fish meal, rice bran, etc.). Besides the use of algae as a protein source for livestock, apply many of the health benefits to animals (i.e. improved immune response, improved fertility, better weight control, healthier skin and a lustrous coat [22, 25] thus improving the product for subsequent human consumption of meat and milk. Adding algae to the diet of cows resulted in a lower natural breakdown of unsaturated fatty acids and a higher concentration of these beneficial compounds in meat and milk. Another important example is the feeding of poultry with algae rich in omega-3 fatty acids, which flows through the food chain, placing this cholesterol lowering compound in eggs [20].

Algae for fish and shellfish consumption

Microalgae are essential during the processes of hatchery and nursery of bivalves, shrimp, and some finfish cultures. Microalgae are also used to produce zooplankton, typically rotifers, which are fed to the freshly hatched carnivorous fish [20]. In 1999, the use of microalgae in aquaculture was reported to be divided as 62% for mollusks, 21% for shrimps, and 16% for fish.

Algae based Chemical industry options

Algae also, used to produce some of the important small platform chemicals for their industry, like ethanol and butanol. Other projects, such as producing bio-plastics from algae (Cereplast) and paints (Algicoat) [12].

Fertilizer

Historically, seaweed had been used as a fertilizer worldwide in coastal regions, mainly for its mineral content and to increase the water-binding capacity of the soil. Microalgal species that fix nitrogen are important, especially in rice cultivation. Both macro- and microalgae could contain compounds that promote germination, leaf or stem growth, flowering or might be used as a biological protection agent against plant diseases [22].

After the extraction of oil or carbohydrates from both seaweed and microalgae, most of the nutrients are still present in the left-over biomass. One potential market for this nutrient-rich biomass is as biofertilizer [26].

Fibers for paper

Most plant cell walls consist of cellulose, but in algae cell coverings are very diverse. Some algae species have intracellular walls, or scaly cell walls made of deposits of calcium carbonate or silica, but most algae derive structural strength from continuous sulphated polysaccharides in marine algae; other possibilities being cellulose, carrageenan, alginate and chitin [22]. Cellulose-containing algae could potentially be used as a renewable feedstock for paper production as the strong green colour of algae is more difficult to bleach than wood fibers but, although algae are generally known for their low cellulose and hemicellulose content, there are a few examples of research into the use of algae as a non-wood fiber source [11].

Bioplastic polymers

Poly- hydroxybutyric acid (PHB) is a naturally occurring polymer found in a large number of photosynthetic and non-photosynthetic bacteria. It serves as a carbon reserve material in prokaryotes and as does starch in eukaryotic plants. PHB can be produced by cyanobacteria such as *Spirulina* and *Dunaliella* as a biodegradable thermoplastic Polymer (Figure 7) [12].

Figure 7. Algal bio-plastic tableware (http://cleantechnica.com)

Glycerol

The microalga *Dunaliella salina* might contain up to 40% of its dry weight as glycerol. However, the low price of glycerol (as a co-product of biodiesel production) means that the algal product would not be competitive [11].

Table 4. Aforementioned commercial bio-products from algal biomass and their sources

Product	Comments	Source
Biodiesel	Mainly extracted from *Chlorella*, *Spirulina*, and *Dunaliella*	[12]
Hydrocarbons	Mainly extracted from *Botryococcus*	[17]
Ethanol	*Scenedesmus*, *Chlorella*	[12]
Bioelectricity	Most of algae	[11]
Algae for human consumption	*Spirulina*, *Chlorella*, *Dunaliella*, *Aphanizomenon*, *Haematococcus*, *Crypthecodinium*, *Shizochytrium*	[14]
Staple food	Mainly *Spirulina*	[28, 29]
Polyunsaturated fatty acids	diatoms, *crysophytes*, *cryptophytes* , *dinoflagellates*	[21, 28]
Agar	Mainly extracted from *Gelidium* and *Gracilaria*	[22]
Carrageenan	Mainly extracted from *Eucheuma*, *Kappaphycus*	[22]
Alginate	Mainly extracted from *Laminaria*, *Macrocystis*, *Lessonia*, *Ascophyllum* and others.	[22]

Product	Comments	Source
Pigments	Mainly from *Dunaliella*, *Haematococcus* and others.	[22]
Cosmetics	*Arthrospira* and *Chlorella* and others	[21, 30]
Algae for feeding livestock	*Aphanizomenon, Dunaliella, Spirulina* and others	[12, 20]
Algae for feeding fish and shellfish	*Dunaliella, Spirulina* and others	[20]
Fertilizer	*Many genera*	[26,31]
Fibers for paper	*Spirulina* and *Dunaliella* and others	[12,32]
Glycerol	*Dunaliella salina*	[11, 12]

SUMMARY

The macro and micro algal population of aquatic environments provide a vast genetic resource and biodiversity. This feature alone suggests that these organisms had considerable potential for offering new chemicals, materials and bioactive compounds. There are many conflicting statements on the potential of micro-algae for high biomass production, but there is a general agreement that the current production systems are not economically viable for biomass production alone. The macro-algal seaweeds, whilst used for some specialized applications, are also expensive to farm and harvest offshore. There are few clear drivers for using algal species as biomass for bioenergy, except in specific circumstances such as maritime communities with no access to productive agricultural land or alternative energy sources. Additional value products from the micro-algae, such as chemicals, can increase the cost competitiveness.

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