Microalgae: The Basis of Mankind Sustainability

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Abstract

Microalgae were the basis of life into the planet, but only recently these microorganisms are exploited at a commercial scale. Thus, the production of pharmaceuticals, cosmetics, feed, and foods from microalgae is today a commercial reality increasing year by year. Additionally, microalgae have been proposed to be used to enhance the sustainability of existing industrial activities, as wastewater treatment and biofuel production. In this way, the utilization of microalgae at a large scale is considered a green revolution in the sustainability of mankind. This chapter is focused on reviewing the real contribution of microalgae to human activities. The last improvements of technologies and its uses, in addition to still existing bottlenecks for the massive exploitation of these microorganisms, are reviewed.

Keywords: microalgae, sustainability, food production, biomass, bioenergy

1. Introduction

Microalgae and cyanobacteria are photosynthetic microorganisms performing oxygenic photosynthesis. There are more than 30,000 species catalogued and classified; however, less than a hundred have been studied, and no more than 20 are actually under commercial exploitation [1]. These microorganisms were responsible for larger transformations into the planet as oxygen production in addition to Fe and S oxidation, which allows the explosion of life into the planet [2]. Moreover, these microorganisms were responsible for CO_2 reduction in past ages transforming it into calcium and diatom rocks, in addition to fossil fuels that we are using now. Today microalgae and cyanobacteria are responsible for most of the solar energy capture and oxygen production into the planet. Thus, these microorganisms are today the

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basis of food chain in aquatic systems, thus being a fundamental pillar in the sustainability of the planet. Moreover microalgae and cyanobacteria are majorly responsible for CO_2 transformation to biomass into the planet, thus also contributing to the reduction of the global warming effect [3].

Microalgae are capable of growing in largely different ambients, from warm areas in the tropic and deserts to cold areas in the high mountains and poles. Some of the major advantages of these microorganisms are that they do not require fertile land or usable water and they can grow in contaminated waters [4]. These capabilities allowed humans to use microalgae and cyanobacteria for centuries. Thus, *Spirulina* was harvested by ancient Mexico populations as food especially in the area of Lake Texcoco, a similar scenario taking place in Africa in the areas surrounding Chad Lake, where this fast-growing cyanobacterium grow naturally [5]. Also, different types of cyanobacteria were used, and still they are used today in agriculture to fix atmospheric nitrogen to enhance the production of rice among other crops. The most relevant but usually forgotten contribution of microalgae to mankind is the natural production of feed for aquatic systems used in aquaculture where millions of tons of fish and molluscs are produced on the basis of phytoplankton naturally occurring both in the oceans and lakes [6].

Due to the high capacity to produce biomass and its highly interesting composition, containing proteins rich in essential amino acids, high-value lipids and fatty acids, and valuable carbohydrates, the industrial production of microalgae attracts special attention. The first reports about the production of microalgae were published in 1950 [7] focusing on the utilization of tubular photobioreactors for the production of *Chlorella* in 50 L reactors. Later the production of microalgae in raceway reactors was reported by Oswald mainly for wastewater treatment [8]. These raceway reactors have been applied from the 1970s to produce *Spirulina* at a commercial scale and from the 1980s to also produce *Dunaliella* as a source of β-carotene, these being two nice examples of microalgae-based bioprocesses. Still today these are the strains and photobioreactors largely used worldwide, in addition to *Chlorella*, representing about 20,000 t/year of biomass production. This production capacity is not too much in comparison with other biomasses or crops, but it is increasing more than 10% annually [9]. Thus, in the last 20 years, the number of strains produced at a commercial scale includes *Haematococcus*, *Euglena*, and *Nannochloropsis*, among others, for applications related to feed, foods, cosmetics, and pharmaceuticals.

In this chapter, the major factors influencing the production of microalgae and the technologies used to produce it at a large scale are summarized. Future trends and contributions of microalgae to mankind in the next years will be also discussed to show the relevance of this "green revolution."

2. Major factors in microalgae production

Microalgae are photosynthetic microorganisms equivalent to plants but with some differences: (i) they are micro with size ranging from 2 to 20 μm and usually grow in water bodies; (ii) they grow much faster than higher plants with duplication times lower than 1 day; (iii) they do not have roots or large structures, their photosynthetic efficiency being much higher than higher plants; and (iv) they require a supply of large amounts of nutrients, mainly CO_2, N, and P, to maximize their performance. Thus, on the basis of these differences, the microalgae production systems have been developed to satisfy the requirements of microalgae cells to achieve the maximal production capacity at a lower cost.

2.1. Light availability

Light is the main factor in determining the performance of microalgal cells. For the entire solar spectrum, the photosynthetic apparatus only use the light at wavelengths from 400 to 700 nm (photosynthetically active radiation, or PAR), which is being saturated at relatively low irradiances ranging from 100 to 200 μE/m²·s. Because the solar radiation achieves values more than times higher than this saturation value, the photosynthetic apparatus can be oversaturated or photoinhibited at outdoor conditions. To solve this problem and enhance the performance of microalgae cultures, the solar radiation must be "distributed" between the larger number of cells and surface as possible. Thus, different designs of photobioreactors have been proposed. Whatever the photobioreactor design, in microalgae cultures the light impinging into the reactor surface (I_0) is attenuated along the culture as a function of the path length (p), biomass concentration (C_b), and extinction coefficient of the biomass (K_a). This attenuation makes that light gradients exist, the cells being exposed to different light conditions according to the light profile and mixing [10]. Although rigorous calculations about light profile in microalgae cultures have been performed, to approximate the average irradiance at which the cells are exposed to in whatever photobioreactor the equation proposed by Molina is really useful and comfortable (Eq. (1)) [10]. **Figure 1** shows as the higher the biomass concentration the higher are the gradients at which the cells are exposed to inside the cultures, these being higher also the higher the culture depth. Following this argument it would be recommendable to use thin-layer reactors with low biomass concentrations to minimize the light gradients inside the cultures, but in this scenario, the production capacity is largely reduced; then an optimal solution must be found. For this, the optimal design of the reactor maximizing the light on the reactor surface (I_0) while optimizing the culture depth (p) and its adequate operation to maintain the optimal biomass concentration (C_b) is the challenge:

$$I_{av} = \frac{I_0}{(K_a \cdot p \cdot C_b)}\left(1 - \exp\left(-K_a \cdot p \cdot C_b\right)\right) \tag{1}$$

According to the limitations of photosynthetic apparatus, it has been reported that microalgae can achieve a maximal photosynthetic efficiency (PE) of 5% from global radiation. This means that microalgae are able to accumulate up to 5000 GW/ha·year in tropic areas if production systems achieving 5% PE are operated, whereas this value reduces to 400 GW/ha·year when considering 1% PE and temperate locations with low solar radiation availability (**Figure 2A**). Considering the heat value of the microalgae biomass of 20 MJ/kg, this means that the amount of biomass than can be produced per unit area and year is limited by the solar radiation availability at the selected location and the photosynthetic efficiency achieved in the used production system. **Figure 2B** shows that biomass productivity values up to 250 t/ha·year can be obtained in tropic areas if 5% PE is achieved in used systems, whereas this productivity decreases to 20 t/ha·year in temperate areas with low solar radiation if 1% PE is achieved.

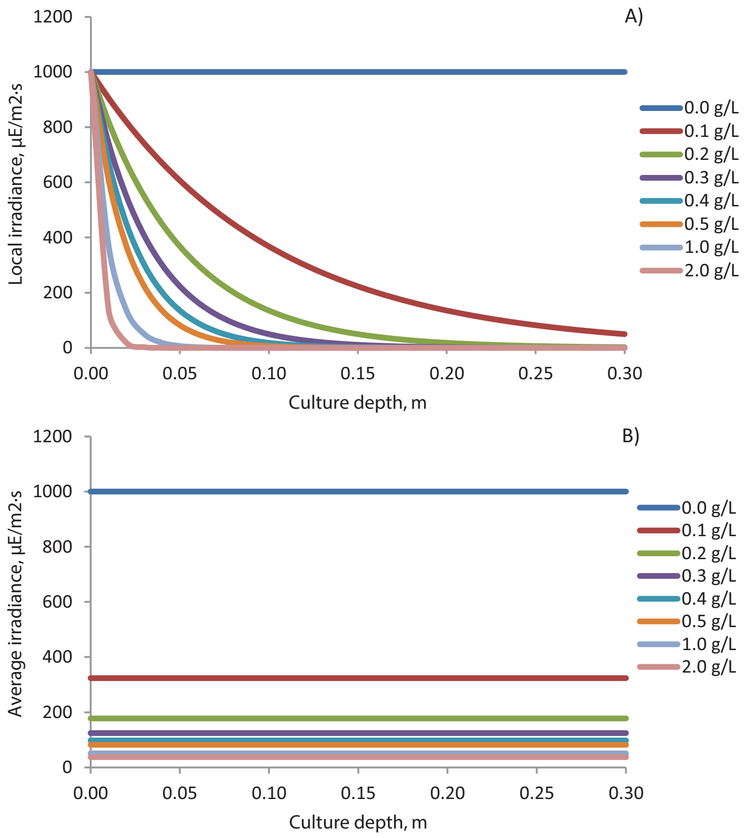

Figure 1. Variation of irradiance as a function of culture depth and biomass concentration in raceway reactors considering a solar irradiance on the reactor surface of 1000 $\mu E/m^2\cdot s$ and extinction coefficient of the biomass of 0.1 m^2/g. (A) Variation of local irradiance at different culture depths. (B) Average irradiance value estimated for the entire culture.

These values are higher than productivities of corn (12 t/ha), wheat (8 t/ha), or soya (6 t/ha), thus showing that microalgae biomass is a realistic food alternative. Moreover, the large biomass production capacity of microalgae-based processes does that these microorganisms were considered a real alternative to energy crops to produce biofuels [11]. These figures confirm that although solar radiation availability is a major factor in the production of microalgae biomass, the optimization of the used system and at the end the photosynthetic efficiency achieved is also highly relevant in the final biomass production capacity.

2.2. Nutrient supply

Microalgae biomass is mainly composed of carbon (45%), nitrogen (7%), and phosphorus (1%) in addition to oxygen and hydrogen that are directly obtained from the hydrolysis of water. However, the first ones must be supplied, the required amount of these nutrients being directly

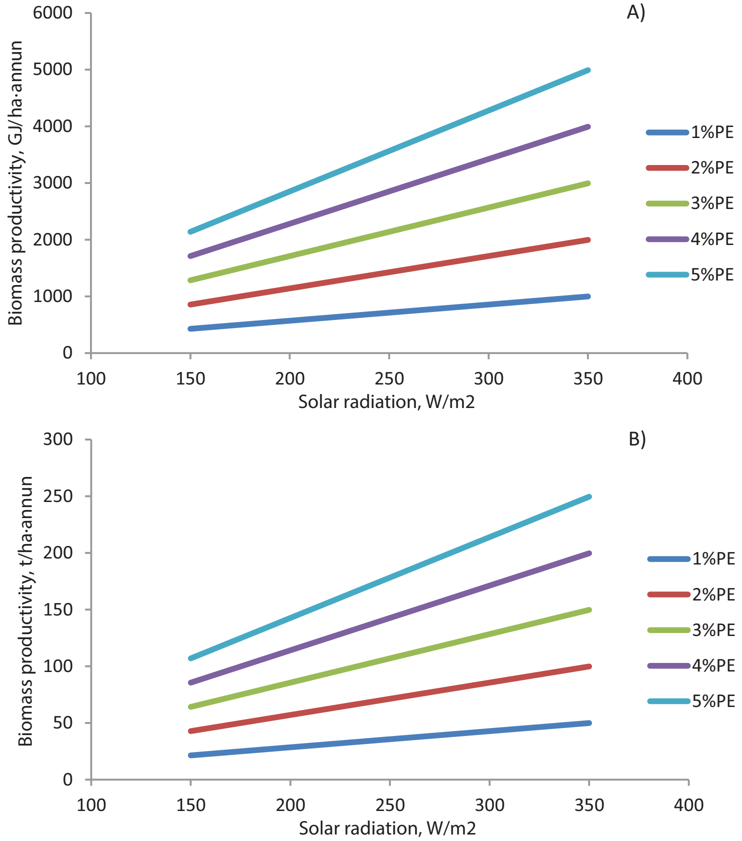

Figure 2. Variation of biomass production as a function of solar radiation availability and photosynthetic efficiency achieved in the production system. (A) Daily biomass productivity per unit surface. (B) Annual biomass productivity per unit surface.

proportional to the microalgae biomass capacity required. Carbon can be supplied as carbonate or bicarbonate, but the utilization of CO_2 is greatly recommended because it allows at the same time to control the pH of the cultures. Stoichiometrically up to 1.8 kg of CO_2 is required to produce 1.0 kg of microalgae biomass, although this value can be modified according to the precise elemental composition of produced biomass. **Figure 3** shows that CO_2 fixation capacity of microalgae cultures is directly a function of solar radiation availability and photosynthetic efficiency achieved in the production system. Values ranging from 190 to 450 tCO_2/ha·year can be fixed in tropic areas at photosynthetic efficiencies ranging from 1 to 5%, whereas in temperate areas with low solar radiation availability, these figures reduce to values ranging from 40 to 90 tCO_2/ha·year at the same photosynthetic efficiencies. Not only pure CO_2 but also whatever gas containing CO_2 can be used to produce microalgae; thus, it is being proposed to use flue gases from power stations, biogas from anaerobic digestion, or fermentation gas from

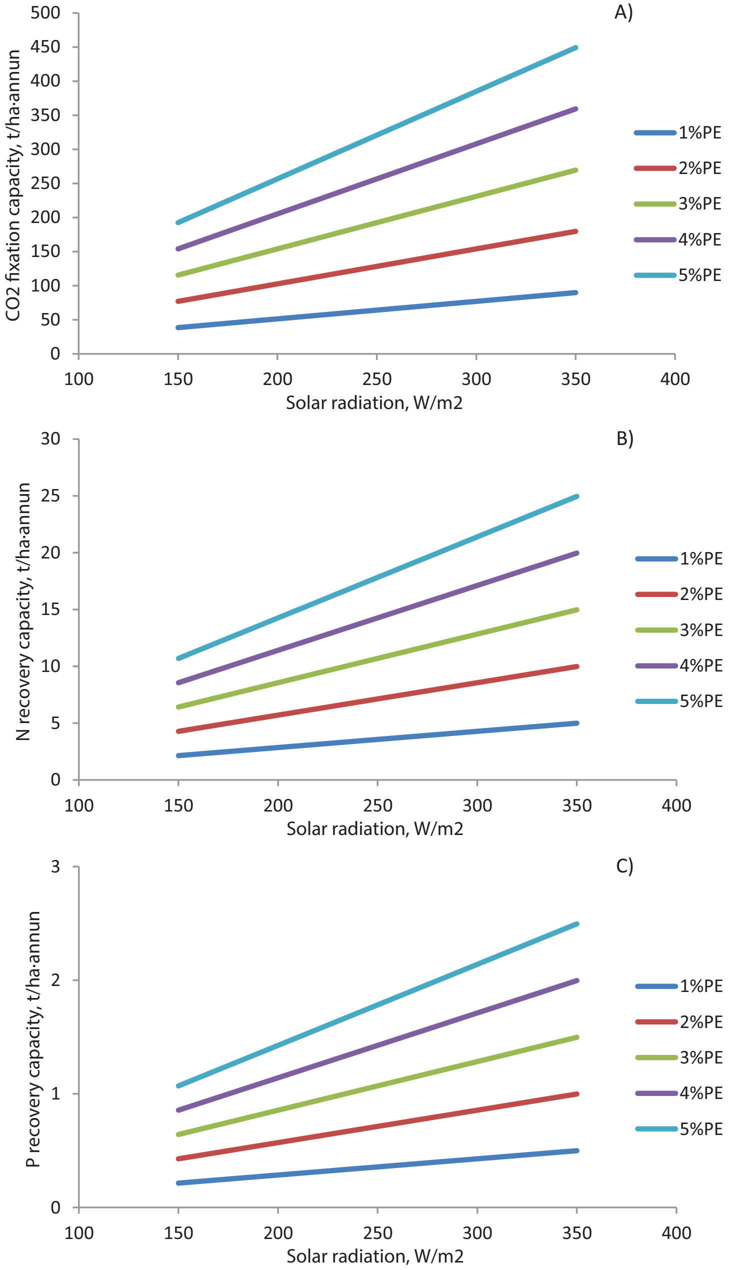

Figure 3. Variation of CO_2, N, and P recovery capacity as a function of solar radiation availability and photosynthetic efficiency achieved in the production system. (A) CO_2 fixation capacity, (B) N recovery capacity, and (C) P recovery capacity.

ethanol production to produce microalgae biomass at the same time that reducing CO_2 emissions of these industries [12]. When using whatever gas to supply CO_2 to microalgae cultures, two main aspects must be considered: (i) to use efficient systems capable to transfer more than 90% of CO_2 contained into the flue gas to the microalgae culture and (ii) to be sure that the gas does not contain toxics that can damage the growth of microalgae cells (SOx, NOx) [13]. Related to the supply of CO_2 is the removal of oxygen because it is produced at the same rate that CO_2 is consumed, it accumulating into the culture if not removed. Most of microalgae strains are inhibited by oxygen at dissolved oxygen concentration higher than 200%Sat. (c.a. 20 mg/L); thus, adequate oxygen removal systems must be installed and operated to overpass these phenomena [14]. In general, the optimization of mass transfer capacity is a key factor in the performance of whatever microalgae production system [15].

In addition to carbon, nitrogen and phosphorus are the most relevant nutrients required for the production of microalgae. About 0.1 kg of N and 0.01 kg of P are required to produce 1 kg of microalgae biomass. On the basis of biomass production as a function of solar radiation and photosynthetic efficiency, **Figure 3** shows that the N recovery ranges from 2 to 10 tN/ha·year in temperate climates with low solar radiation and from 5 to 25 tN/ha·year in tropic areas, when the photosynthetic efficiency modifies from 1 to 5%. In the same way, the P recovery ranges from 0.2 to 1.1 tP/ha·year in temperate climates with low solar radiation and from 0.5 to 2.5 tP/ha·year in tropic areas, when the photosynthetic efficiency modifies from 1 to 5% (**Figure 3**). Soluble forms of these compounds are produced at a large scale worldwide because they are pillars of the food production by agriculture. Phosphorous reservoirs are limited, and some reports are advertising about the crash of the actual food production system based on phosphorus [16]. To transform P-rich rocks into fertilizers, huge amount of energy is required, whereas nitrogen production systems use atmospheric nitrogen but also are consuming large amounts of energy to transform it into ammonia and nitrate by the Haber process. To avoid these problems, the recovery of nitrogen and phosphorus from wastes and residual streams is mandatory, microalgae being specialists on these processes [17]. Thus, microalgae are capable to completely remove N and P contained in wastewater streams, only using solar energy into the process, at the same time producing valuable biomass. The development of microalgae-based treatment processes is a key issue in this field [18].

2.3. Culture conditions

Microalgae as whatever other microorganisms have optimal conditions that must be known in order to maximize their performance. Optimal salinity, temperature, and pH are strain specific, and the production systems must be adequately designed/operated to maintain it at optimal values. Regarding salinity, although some microalgae can tolerate large variation of salinity, usually freshwater (i.e., *Scenedesmus*, *Chlorella*, *Spirulina*) or seawater (i.e., *Nannochloropsis*, *T-ISO*, *Tetraselmis*) strains are selected according to the salinity of water to be used. Additionally, some hypersaline-tolerant strains can be also produced (i.e., *Dunaliella*), on these conditions the probability of contamination by other strains being reduced. Regarding temperature, most microalgae grow well in the range of 20–30 °C. Over this value, only some extremophile strains show acceptable growth, including some *Scenedesmus* strains and some cyanobacteria as *Anabaena* [19, 20]. Below the optimal temperature, the growth is reduced, but over the critical one, the culture dies; by this reason to avoid overheating of the cultures is mandatory in whatever microalgae production system. Regarding the pH, it can be controlled by providing acidic solutions to the culture medium, but usually the injection of CO_2 is used to reduce the pH and avoid carbon limitation at the same time. The optimal pH for most of the microalgae strains ranges from 7 to 8, although some cyanobacteria show optimal performance at pH up to 10 [19]. To provide CO_2 for pH control is an engineering problem that must be adequately optimized to minimize the amount of CO_2 consumed while increasing the biomass productivity of the system, always considering the cost of infrastructure and energy consumption involved [13]. To ensure that microalgae cultures are only light limited, the supply of CO_2 is mandatory; this is the reason why most of the production systems worldwide do it.

To provide optimal culture conditions at a laboratory or small scale is quite simple although it is expensive. However, at large-scale and outdoor conditions, to accurately control the culture conditions is simply impossible. As example to control the temperature in large reactors requires large investments and high energy usually it being disregarded, strains to be produced being selected to optimally growth at the ambient temperature prevailing in the selected location. In the case of pH, the injection of pure CO_2 can summarize up to 30% of the overall biomass production cost then the utilization of flue gases or residual streams containing CO_2 being recommendable [21]. Anyway, when considering the control of culture conditions, three time scales must be considered: (i) annual basis that means the mean values of environmental conditions prevailing in the selected location, (ii) daily basis that considers the hour-by-hour variation of environmental conditions due to the variation of solar radiation, and (iii) mixing time that means the time to completely mix the system it influencing the existence of gradients of culture conditions along the reactor. Advanced control methods are being applied now to the industrial production of microalgae to reduce cost and improve the performance of microalgae-based processes [22]. Only an in-depth analysis of main culture conditions and its optimization along the different time scales will allow to maximize the performance of whatever microalgae-based process.

3. Photobioreactors and large-scale facilities

Microalgae production is a process that must be adequately planed and performed. Major steps involved in whatever microalgae production process include (i) preparation of culture medium, (ii) production of biomass into photobioreactors, (iii) harvesting of biomass, (iv) treatment of used water for recirculation or disposal, and (v) stabilization of produced biomass or transformation into end products. The core of the process is the photobioreactor in which the microalgae biomass is produced. Large bibliography is already available about photobioreactor designs and operation, here only a comparison of most used technologies being included [23].

3.1. Open reactors

Open reactors are the most extended for the production of microalgae, more than 90% of microalgae biomass worldwide being produced in these reactors. They are basically large water reservoirs with low depth to facilitate the light penetration and increase the biomass productivity. Raceway reactors are the most extended technology but also simple open systems are also used (**Figure 4**). Major advantages of raceway reactors are its low cost, below 10 €/m^2, and easy scale-up, single units up to 5000 m^2 being used at a commercial scale. Another advantage of this technology is its low energy consumption, below 1 W/m^3; thus it is being recommended for low-value applications and the production of biofuels [24]. The major disadvantages of raceway reactors are related to the scarce control of culture conditions and the easy contamination of the cultures. By these reasons they are mainly used to produce strains growing under extreme conditions as high pH (*Spirulina*) or salinity (*Dunaliella*).

Examples of large facilities producing microalgae using raceway reactors are available worldwide. Companies such as Cyanotech (USA; www.cyanotech.com), Earthrise Nutritionals (USA; www.earthrise.com), Parry Nutraceuticals (India; www.murugappa.com), and Myanmar Spirulina Factory (Myanmar) are some of larger producers of *Spirulina* worldwide using raceway reactors in facilities from 10 to 100 ha. These reactors are also used by different companies to produce *Dunaliella* at a large scale such as Nikken Sohonsha Corp. (Japan; www.chlostanin.co.jp), Betatene (Australia; www.betatene.com.au), Nature Beta Technologies (Israel), ABC Biotech Ltd. (India), Tianjin Lantai Biotechnology (China), Western Biotechnology Ltd. (Australia), and Aqua Carotene Ltd. (Australia). The design of raceway reactors is being reviewed in the last years to enhance its performance. Thus, the hydrodynamics, mass transfer, and power consumption are major aspects to be improved [14, 25, 26]. Because these reactors are the most extended worldwide and the technology currently used is performing nicely at a large scale, most of the new microalgae-based processes use this type of photobioreactors. Thus, the development of microalgae-based wastewater treatment or biofuel production processes, and the production of low-cost biomass for biofertilizers and feed, currently uses these reactors [24, 27].

3.2. Closed reactors

Closed reactors are now being used to produce microalgae strains that do not tolerate extreme conditions but contain valuable compounds, thus its price being high. Several designs have

Figure 4. Image of some photobioreactors used for outdoor production of microalgae at a large scale. A raceway reactor of 20 m^3 as an example of open reactor (left side) and ten tubular reactors of 30 m^3 as an example of tubular reactors (right side). All of them installed and operated at Estación Experimental Las Palmerillas (Fundación Cajamar), Almeria, Spain.

been proposed as bubble columns, helical systems, or flat panels, but from all of them, the most extended at a commercial scale are the tubular photobioreactors (**Figure 4**). The basic principle of whatever close reactor is to isolate the culture from the surrounding ambient, thus minimizing contamination problems and avoiding a better control of culture parameters. In the tubular reactors, the culture is continuously recirculated along the solar receiver, which is designed to maximize the interception and utilization of solar radiation. These reactors allow to produce almost whatever strain, including sensible strains such as *Haematococcus* or *Porphyridium*, and to achieve high productivity values, higher than 1 g/L·day, by adequate control of culture parameters. However, they have also disadvantages related to higher cost, higher than 10 €/m^2, and energy consumption, higher than 100 W/m^3, difficulty of scale-up, and reduction of performance by biofouling [23, 28, 29].

Tubular reactors are used mainly to produce high-value biomass for human applications. Thus, companies such as I'age vertd (France; www.agevert.com), SECIL (Portugal), and Roquette Klötze (Germany) produce *Chlorella* for food markets at facilities around 1–2 ha size. Other companies such as Mera Pharmaceuticals (Hawaii, USA) and Algatech Algaltechnologies (Israel; www.algatech.com) are producing *Haematococcus pluvialis* also using tubular photobioreactors. The larger facility based on this technology has been installed in China with up to 20 ha also to produce *H. pluvialis*. Facilities based on tubular photobioreactors are now being installed worldwide, its size and capacity increasing year by year. This is due to the combination of involvement of engineering companies and the requirement of microalgae biomass produced under controlled conditions according to Good Manufacturing Practices (GMP) for human consumption. The utilization of new materials reducing fouling and increasing the stability of the production systems is a major challenge for this technology [30].

4. Microalgae applications

4.1. Microalgae-based market analysis

Microalgae-based products include a large portfolio of applications, some of them only potentially indicated whereas others being realistic at a commercial scale. These applications can be divided in four main groups related to the safety requirements of different markets: (i) production of energy, mainly biofuels; (ii) products for agriculture, such as biostimulants, biopesticides, and bioplastics; (iii) production of feeds for farms and aquaculture; and (iv) products for human consumption, mainly foods and nutraceuticals [31]. When comparing the market size of the different markets, it is observed that biofuels market is requiring enormous productions, higher than 10^7 t/year, that today are far from the actual microalgae biomass production capacity, up to 10^4 t/year (**Figure 5**). The actual production capacity is closely related to human applications, requiring around 10^4 t/year, this being slightly lower than required capacity of agriculture uses, up to 10^5 t/year, and feed applications, of around 10^6 t/year. Regarding market price, the actual microalgae biomass production cost ranges from minimum 5 €/kg in raceway reactors to 12 €/kg in tubular photobioreactors [32]; the market price must be higher than production cost to be economically feasible. Results show as only human uses, the production of feed additives and some applications related to agricultural uses, as the production of biostimulants and biopesticides, have market prices higher than the actual production cost (**Figure 5**). From this analysis, it is easily concluded that only these applications are realistic today. Thus, the market value of human-related products exceeds 10^3 M€/year, for agriculture-related products 10^4 M€/year, and for aquaculture-related products up to 10^5 M€/year, demonstrating the relevance of these sectors in the future (**Figure 5**).

To expand the application of microalgae-based processes to other fields, the microalgae biomass production cost must be reduced by one order of magnitude, whereas the production

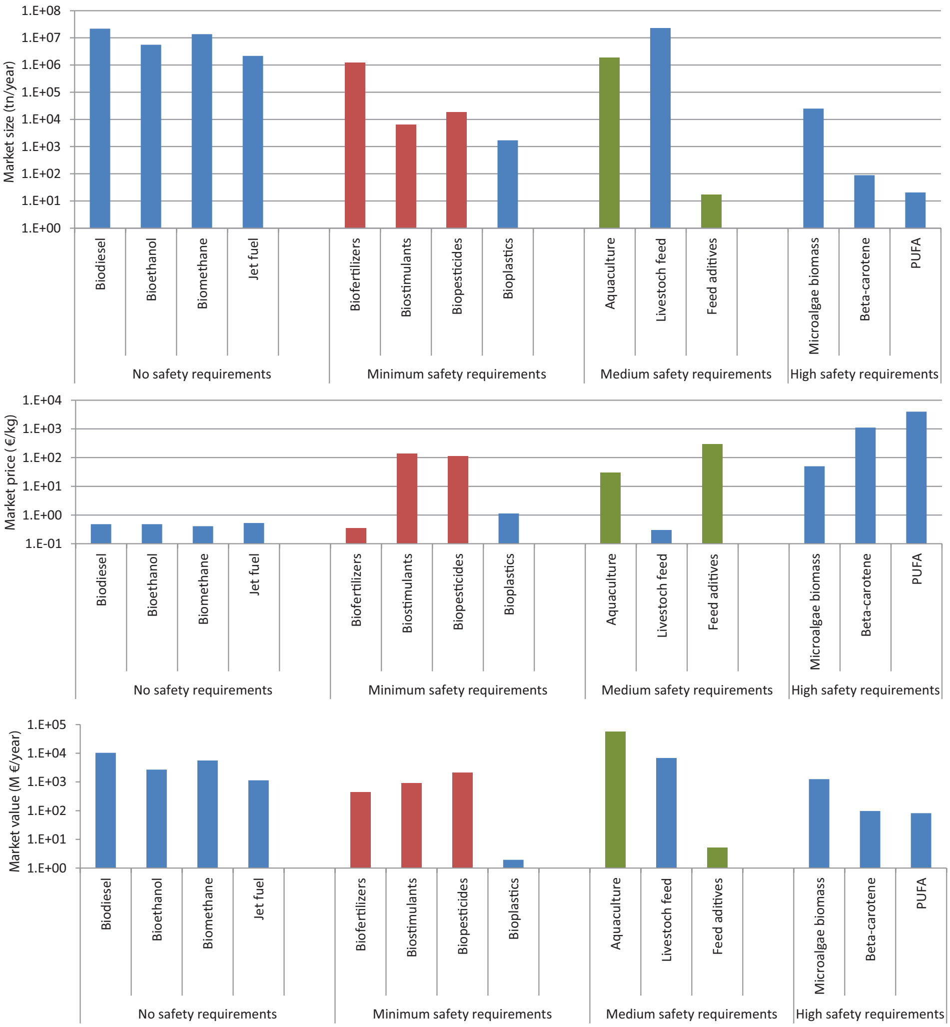

Figure 5. Market analysis of microalgae-based products. Data obtained from Refs. [31, 32, 35].

capacity must be increased by at least three orders of magnitude; that is not an easy challenge. The microalgae biomass production cost can be greatly reduced if the productivity of the actual production systems is enhanced, the facilities are scaled-up, and the coupling with other processes as waste treatment is performed, thus this being the challenge in the future [21, 33]. Regarding the increase of production capacity, only the development of new schemes, using more robust and scalable technologies, in addition to the utilization of more resistant and productive microalgae strains will really allow to significantly increase the production capacity.

4.2. High-value applications of microalgae

High-value applications of microalgae are mainly related to direct human consumption as foods, nutraceuticals, cosmetics, or pharmaceuticals [34]. Microalgae biomass contains proteins, lipids, and carbohydrates, all of them of high quality for human consumption. Thus, microalgae biomass contains large amounts of essential amino acids and polyunsaturated fatty acids, in addition to sterols and carotenoids with antioxidant activity, thus this biomass being considered as a superfood [35]. In this sense, in 2012, the EU adopted a strategy focused to innovate through the impulse of bioeconomy sector, the "Blue bioeconomy" being one of the pillars of this strategy which is being directly related to the production of microalgae as a source of high-value molecules for human uses [36]. Microalgae have been reported to be a "sustainable" source of food and nutraceuticals for human uses, by its higher nutritional and functional properties versus conventional crops as cereals and vegetables and its lower land requirement also reducing the risks related to food insecurity supply in the world [37].

Microalgae biomass can be used as food directly, in different mixtures with other foods, or alternatively by consuming extracts of valuable compounds. Dry biomass of *Chlorella* and *Spirulina* is commercialized as powder or in capsules, also it being incorporated to juices, cakes, pasta, and other foods to enhance the nutritional value or provide healthy properties as antioxidant, among others. Regarding extracts, carotenoids as astaxanthin and β-carotene are extracted from the biomass of *Haematococcus* and *Dunaliella*, generally using supercritical CO_2, and incorporated to suspension as health enhancer. Other compounds as polyunsaturated fatty acids, i.e., eicosapentaenoic cid (EPA), arachidonic acid (AA), and docosahexaenoic acid (DHA), are also extracted mainly from the biomass of marine strains, as *Nannochloropsis* and T-ISO, also mainly using supercritical CO_2, and incorporated to oils and capsules for human consumption. Special mention is the case of the production of docosahexaenoic acid (DHA) from *Schizochytrium* by the company Martek that is incorporated to infant milks in a high-value application.

Major concern about the incorporation of microalgae biomass to foods is related to EU regulation. In spite of largely reported advantages of microalgae biomass for human consumption, only the microalgae now generally recognized as safe (GRAS) can be sold for human consumption. These only include *Chlorella*, *Spirulina*, *Dunaliella*, and *Haematococcus*. Other microalgae must be registered as novel food as recently performed by Fitoplancton Marino regarding *Nannochloropsis*. Anyway, independent of the strain to be produced, the overall production system must be approved for "food industry"; this certification involves the materials, systems, and protocols used during the production process. In this way, the involvement of food companies in the development of microalgae-based processes is mandatory.

A wide analysis of microalgae-based products for the food and feed sector in Europe has been recently published [32]. According to this review, the global marine biotechnology market in 2011, with microalgae as its main component, was estimated to be €2.4bn, with an expected yearly growth of 10%. Most of this market is related to the health food market as dietary supplements; by these reasons large companies in the food ingredients market as BASF, Unilever, and Dow Chemical are now involved in projects related to microalgae production.

4.3. Low-value applications of microalgae

Low-value applications of microalgae are related to biofuel and biofertilizer production, but all of them are only sustainable if coupling with wastewater treatment [38]. Wastewater treatment is a crucial challenge for the sustainability of human activities. The release of wastewater is continuously increasing by the increase of population and healthy habits. However, wastewater is not always adequately treated; thus, worldwide more people die by diseases related to water contamination that is caused by violence including wars. Moreover, the release of untreated wastewater to environments causes eutrophication problems which are seriously damaging ecosystems. To avoid these problems, the wastewater must be adequately treated to remove pollutants and release water in safe way [39]. Conventional systems based on activated sludge consist of a series of operation units focused on transforming the organic matter into CO_2 that is emitted to the atmosphere, nitrogen and phosphorus being also released to the atmosphere as N_2 or otherwise it being accumulated into the sludge that is finally subject to anaerobic digestion to produce biogas, normally without recovering N or P. Moreover, to perform this process, a large amount of energy is required, up to 0.5 kWh/m^3, the cost of the overall treatment summarizing up to 0.2 $€/m^3$. The concern about environmental protection is forcing the governments to reduce the limits of N and P content in wastewater for safe release to the environment; then additional treatment processes are necessary, all of them consuming larger amounts of energy and imposing higher costs.

As an example, a company as Aqualia from FCC Group, which is operating more than 250 wastewater treatment plants in Europe, is treating up to 500 Mm^3/year of wastewater. The business related to this activity summarizes more than 100 M€ per year and consumes up to 250 GWh/year, equivalent to the overall electricity consumption of Spain in one day. Moreover, this energy and its CO_2-related emissions are mainly used to dissipate to the environment more than 25,000 tN/year and 5000 tP/year. This large amount of nutrients is sufficient to produce more than 0.5 Mt/year of microalgae biomass, 20 times larger than the actual worldwide microalgae production. The coupling of microalgae production with wastewater treatment allows to reduce the energy and cost of wastewater treatment at the same time that recovers the nutrients contained in wastewater and reduces the production cost of microalgae biomass, to increase the performance of actual technology used being a major challenge in the future [18, 40, 41].

Microalgae can perform the treatment of wastewater in consortia with bacteria. In this technology microalgae perform photosynthesis producing the oxygen required by bacteria to degrade the organic matter to inorganic carbon, nitrogen, and phosphorus that is at the end assimilated by microalgae as valuable biomass [42]. If aeration is not required, the energy cost of wastewater treatment is reduced to half, moreover producing microalgae biomass the net amount of energy obtained at the end of the process being higher than at the beginning by including solar energy, thus being an “energy positive” process. To couple the production of microalgae with wastewater treatment is not a new idea, and it was proposed by Oswald in the 1960s [8]. However, very few real applications of this technology have been carried out at a commercial scale [43]. There are several reasons for that, but the most relevant is the low efficiency of existing technologies, especially requiring large hydraulic retention times of up to 10 days, thus enormous land requirements being imposed. The improvement of operation conditions and the utilization of new photobioreactor designs as thin-layer cascade have been proposed to improve the performance of microalgae-based systems [44]. Recent advances in the design and operation of raceway reactors, coupled with the reduction of energy consumption and hydraulic retention time required to achieve complete removal of contaminants from wastewater, allow Aqualia to develop the first commercial plant based on microalgae for wastewater treatment with up to 10 ha and be able to treat the wastewater of 80,000 inhabitants in Chiclana (Spain) within the ALLGAS project.

Microalgae can be also used to treat other wastewaters from farms, aquaculture, anaerobic digestion, and industry [42, 45–47]. The development of especially designed microalgae-based processes for these sectors, including urban wastewater, is a challenge that can transform the actual energy/resources consuming conventional treatment processes into energy positive and productive systems in a revolutionary transformation of wastes sector. Moreover, the produced biomass is suitable to be used in the production of biofertilizers and feed for animals, thus largely increasing the sustainability of food production now related to the consumption of large amounts of fertilizers, land, deforestation, and water consumption [48, 49].

5. Conclusions

Although microalgae are known for centuries, only recently they are being studied and produced at a commercial scale. The feasibility of these microorganisms to grow at largely different environmental conditions and its high productivity make it as highly relevant for mankind. The knowledge of the main factors governing the production of microalgae allows developing industrial production processes at a commercial scale. Because still the production capacity is low and the production cost is excessive, the applications of microalgae are mainly related to human consumption. However, the improvement of the actual production systems, and especially the development of new technologies and the “domestication” of highly productive strains, will largely increase the production capacity and the portfolio of microalgae-related applications in the future.

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