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Review article

Is exploitation of microalgae economically and energetically sustainable?

Laura Barsanti, Paolo Gualtieri*

C.N.R. Istituto di Biofisica Pisa, Italy

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ABSTRACT

Microalgae are a diverse group of single-cell photosynthetic organisms, both prokaryotes and eukaryotes, which can rapidly grow in a wide range of habitats under photoautotrophic conditions. Recently, microalgae have been the object of increasing interest due to the attractive potential they offer in the current scenario of dwindling energy and food resources. Microalgae are flexible systems with the potential for production of feedstock biomass and high valuable natural products. Their productivities may be further improved with strain selection, genetic amelioration, and process engineering. However, though microalgae are considered the best alternative feedstock for the production of 3rd generation biofuel, the high cost of biomass production and biorefinery currently makes them uncompetitive with the cost of fossil fuels and traditional renewable energy resources. The development of microalgae culture technologies at commercial scale is, therefore, limited to a few profitable facilities around the world, producing very high value products (e.g., carotenoids, poly unsaturated fatty acids, immune-stimulants polysaccharides, etc.), whose high selling price can guarantee the return on investment.

Our review deals with currently known natural high value products from microalgae, divided according to their potential use (i.e., energy- and non-energy based), their target market, and their cost-benefit balance beyond the biomass production. We analyze the economics of algal feedstock production and biorefinery, together with an overall energetic effectiveness of the cultivation process.

1. General considerations

Environmental protection and energy production are among the greatest challenges facing mankind in the 21st century. The global economy is necessarily changing from fossil-based to renewable and bio-based [1]. In a bio-based economy, biomass is valorized and used for the sustainable production of food, feed, chemicals, fuel, power and heat.

Sunlight is by far the most important input of energy to Earth. At sea level, in an ordinary clear day, the average intensity of solar radiation is $< 1\,\mathrm{kW\,m^{-2}}$, > 7500 times the world's total primary energy consumption [2]. Photosynthesis is the only biological process channeling solar energy into the biosphere. Microalgae comprise cyanobacteria plus many phyla of eukaryotes, span all sunlit habitats and have high photosynthetic rates and efficiency [2]. Under natural conditions, their photosynthetic efficiency, i.e., the conversion rate of light energy into biomass energy can be as high as 3% [3], while the efficiency of C3 plants is only about 0.2% [4]. Under optimal growing conditions the theoretical maximum of photosynthetic efficiency for microalgae is about 10% [5], while the theoretical maximum for C3 plants is 4.6% and for C4 plants is 6% [6].

Microalgae use sunlight to grow as a completely exploitable feedstock, consisting of raw biomass, primary metabolites and secondary metabolites. Primary metabolites are necessary for basic survival of the microalgae that use them for energy and tissue construction; these metabolites include oligomeric carbohydrates, most amino acids and proteins, lipids, nucleic acids, vitamins and cofactors, chlorophylls and plastidial carotenoids. High-value secondary metabolites, such as most polymeric carbohydrates, terpenes, lutein, astaxanthin, lectins and most poly unsaturated fatty acid (PUFA) are assembled from primary metabolites fragments, often have vital functions, but are not involved in the development or maintenance of the organism. They are limited in their biological distribution, often species-specific, and most often produced by the microalga for intervention in ecological interactions [7]. Under conditions of stress and/or specific environmental conditions (e.g., lack of specific nutrient, excessive UV radiation, bacteria, competitive species), microalgae react by producing metabolites with variable profiles, accumulating them inside the cell. Examples are *Haematococcus*, which accumulates astaxanthin up to 5.5% of its dry weight [8], and *Nannochloropsis,* which accumulates eicosapentaenoic acid (EPA) up to 12% of its dry weight [9]. Many of these metabolites exhibit important activities as anti-oxidative, anti-inflammatory, antifungal, antibiotic, antiviral, immune-stimulant and antitumor factors, and have the GRAS (Generally Regarded As Safe) designation, which

* Corresponding author at: Istituto di Biofisica, CNR, Via Moruzzi 1, 56124 Pisa, Italy.
E-mail address: paolo.gualtieri@pi.ibf.cnr.it (P. Gualtieri).

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allows their use for animal and human consumption [10].

The metabolic plasticity of microalgae allows qualitative and quantitative tailoring of product synthesis. The production of these compounds can be integrated with bio-remediation, such as CO_2 mitigation and the removal of nutrients (N, P, NH_4^+, NO_3^-, and PO_4^{3-}), metals and heavy metals (Cr^{6+}, Cd^{2+}, Cu^{2+}, Zn^{2+}, Pb^{2+}, Hg^{2+}) from waste effluents [11–15]. Microalgae are capable of enormous CO_2 capture and sequestration with 1 kg of produced biomass potentially per 1.83 kg of recycled CO_2 [16], but actual CO_2 uptake can be lower. For example, 1 kg of *Nannochloropsis gaditana* can fix 1.5 kg of CO_2 in ten days [17]. Microalgae can fix CO_2 also from exhaust fumes and soluble carbonates, if cultivated near CO_2 point sources, such as coal or natural gas power plants or factories [18].

One of the main concerns for biomass production is the life cycle extent, since shorter life feedstocks are more sustainable than longer life ones. Microalgae have the shortest life cycle in all the biomass feedstock, ranging from 1 to 4 days [2], while food crops, as rice and maize, need between 90 and 180 days [19]. Hence, microalgae can grow very rapidly leading to a higher productivity (per unit area per year) in comparison to conventional crops [20]. As an example, *Phaeodactylum tricornutum* cultivated in small scale vertical tubular photobioreactors in Almeria (Spain) has reached biomass productivity of about 100 t dw ha^{-1} yr^{-1} (32 g m^2 d^{-1}) [21], while soybean crops in the USA can reach biomass productivity of 2.6 t dw ha^{-1} yr^{-1} [22,23].

All these positive traits of microalgae indicate promise for exploitation, at least at the small scale of pilot plants, but is it scalable? Large scale microalgal feedstock generation and utilization face formidable challenges. Worldwide increasing demand for microalgae biomass for biofuel has convinced governments to finance home-grown microalgae [24]. An example is the EnAlgae 4-year strategic project launched in 2011 by the EU with the aim of developing sustainable technologies for microalgal biomass production, bioenergy and greenhouse gas mitigation, taking them from pilot facilities to market-place products and services. It brought together 19 research groups (public and private) and 14 independent advisors across 7 EU Member States [25]. Nevertheless, the ability for producers to meet that demand requires development of technology to reduce the cost of production while maintaining and improving the feedstock quality. Sustainability in term of energy cost and environmental impact is still the main bottleneck of microalgae biomass exploitation [26–28].

Table 1 lists some microalgal biotechnology companies, products, target market, and location. Clearly most of the producers focus their efforts on high value microalgal products, with returns high enough to counterbalance the economic disadvantage connected with the production-exploitation of the biomass.

The aim of this review is to explore the currently exploited microalgae products; their final use and target market, i.e., bio-energy, feed and food, chemicals and materials, pharmaceuticals and personal care; and highlight their cost-benefit balance for and beyond biomass production.

2. Microalgae-based products: use, market scenario and market value

Four potential market scenarios, i.e., energy, feed and food, chemicals and materials, pharmaceuticals and personal care, can allocate all the microalgae-based commodities (Table 2). Within these markets, offer and demand for these products could grow substantially in the future. The scenarios, listed in order of decreasing value, are divided in their main sectors. These data refer to the European situation.

Energy is a high-volume commodity market with fluctuating (currently low) fossil fuel prices. The overall energy consumption in Eu-19 in 2015 was about 1150 M Toe (tons of oil equivalents) that correspond to about 500 billion € [29]. The three main sectors of this market are electricity (40%), transport (35%), and heat (25%). The feed and food market is worth about 113 billion € globally. The feed sector is preponderant (about 111 billion €), especially due to the growth of aquaculture fish production, which covers 90% of this sector (about 100 billion €). The chemicals and materials market is worth about 13 billion € globally. Biopolymer products, mostly attributed to the packing industries, dominate the entire chemicals and materials market (86%). The pharmaceuticals and personal care market is a low-volume high-value, equally divided into the two main sectors of beauty-related products and therapeutic compounds, worth 1.2 billion € each [29]. In the U.S.A., the four market sizes are several times larger but with the same lines of business [30].

A large number of potential products can be identified (Table 3), which break out in their use, projected markets and selling prices. Notably, prices from literature data are not uniform; hence, the prices reported in the Table 3 encompass those variations.

Microalgae are currently used as whole microalgae paste (wet or dry biomass) and for the extraction of high value compounds (primary metabolites, secondary metabolites). The target markets differ for the different products; biomass is mainly funneled to Chemicals & Materials market and Bio-Energy, while primary metabolites are used in all markets. Secondary metabolites are mainly funneled into Pharmaceuticals & Personal Care market, with an important role as micronutrients in the Feed & Food market. Selling prices greatly differ between the three product groups, increasing from biomass to secondary metabolites.

Raw biomass can be used as slow-releasing fertilizer for agricultural crops and plants to improve the soil organic matter and its water holding-capacity. The defatted biomass resulting from biodiesel extraction, mixed with water, can be sent to anaerobic digestion to produce biogas; it can be also a source of pigments or other bioactive compounds or as a source of proteins. Residual lipids in the defatted biomass could be upcycled as supplement for animal feed. Moreover, this biomass can be recycled back as nutrients to the microalgae cultivation system [31]. Glycerol, a byproduct of the transesterification of microalgal lipids to biodiesel, can be converted to polymers, solvents, aliphatic polyesters or used to generate electricity directly in biofuels cells [32,33]. The digestate resulting from biogas production is only used as soil fertilizer and conditioner similarly to animal manure. Microalgae biomass is also used as a food supplement for human consumption, as feed in the aquaculture of mollusks, crustaceans and fish, and as a feed additive for cattle, swine, horses, poultry and even dogs and cats [34]. The diverse target markets for these products have similar average selling prices, ranging from 500 € to 1000 € t^{-1}.

Primary metabolites are processed into many different bioenergy and bio-based products [35]. Lipids (including waxes) are extracted for biofuel conversion while polysaccharides can be converted through anaerobic fermentation to hydrogen, ethanol, butanol and organic acids [36]. Glycolipids and phospholipids, soluble proteins, starch and oligomeric sugars are converted into personal care products and pharmaceutical ingredients. Chlorophylls and thylakoid isoprenoids (sterols and primary carotenoids, such as β-carotene and lutein) are used as pigments for paints and polymers. The highest wholesale prices are those of glycolipids, phospholipids and chlorophylls, 10.000 € and 15.000 € t^{-1} respectively, while biofuels (biodiesel, bioalcohol and biohydrogen) have the lowest price, < 1000 € t^{-1}.

Due to the small quantities produced, only high value secondary metabolites such as PUFA and secondary carotenoids are economically viable [37,38]. PUFA and oxylipins are used as nutrition supplement for both humans and animal consumption, because of their cardiovascular health-promoting properties and pro- and anti-inflammatory activity [39]. Secondary carotenoids, such astaxanthin, zeaxanthin and canthaxantin, are only accumulated after exposure to specific environmental stimuli. They are of primary importance in the pharmaceuticals and personal care market because of their anti-oxidant capacity [40]. They are also used as pigments in food and feed, especially for aquaculture and poultry [41]. Sterols are used as cholesterol lowering products and anti-inflammatory compounds [42]. Antibiotic substances