Microalgae as source of biofuel: technology and prospective

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Abstract. Microalgae are autotrophic organisms found in solitary cells or in groups of single cells connected together. Their natural environment are typically freshwater and marine systems. Microalgae produce, via photosynthesis, approximately one-half of oxygen generated on earth while simultaneously consume carbon dioxide (CO₂). Among the technologies being examined to produce green fuels (e.g. biodiesel, bioethanol and syngas), microalgae are viewed by many in the scientific community as having the greatest potential to become economically viable fuels. Nevertheless, to reach economic parity with fossil fuels there are still several challenges to be tackled. These include improving harvesting and oil extraction processes as well as increasing biomass productivity and oil content. All of these challenges can be impacted by genetic, molecular, and ultimately synthetic biology techniques.

1. Introduction

It is estimated that by the 2050 the world population will exceed 9 billion of people from the current 7 billion one [1]. This population growth increases demand, among other human needs, for energy, food, recycled nutrients as well as water. This demand must be sustainable, safe and, most importantly, respecting the planet environment without increasing pollution and/or greenhouse gases such as carbon dioxide (CO₂) and nitrogen oxides (NOx).

A lot of effort is put world-wide in searching of alternatives to the current sources of energy, food and clean water as well as reduction of pollutions. Though this research represents a tough issue, these problems may have a unique solution: large-scale rapid biomass production. To achieve this goal, among the most promising technologies available, the best opportunity is represented by microalgae, which can be defined as microscopic solar-powered carbon dioxide-sequestering and nitrogen-fixing organisms. Microalgae are single-cell life forms; they live in solitary cells (average cell diameter 5-10 μm) or in groups of single cells connected together.

Most of microalgae species are autotrophic. Under natural growth conditions they primarily require three components to produce biomass: water, CO₂ and sunlight. In fact, via photosynthesis they can generate organic molecules and release oxygen using inorganic elements plus solar energy. Microalgae produce approximately one-half of the oxygen generated on earth while simultaneously consuming CO₂ during photosynthesis and fixing NOx during their anabolism. Moreover, biomass from microalgae is a promising source of primary/secondary metabolite products with considerable use in the aquaculture, food additive industry, bio-fertilization, pharmaceutical and cosmetic industry.
[2]. They can also perform biodegradation of organic pollutants and wastewater treatment. Compared to land crops, microalgae are much faster growing, do not require arable soil, costly irrigation and fertilizers and their growth is not season-dependent under appropriate conditions. Furthermore, biomass generated by microalgae is relatively easy to be collected and transformed since it represents an homogenous raw material that does not need several costly downstream processes due to the absence of macrostructure (e.g. vascular systems, leaves, roots, bark etc.) as compared to terrestrial crops. Although large-scale microalgae cultivation dates back to 1960, major drawbacks of microalgae production still remain [3]. Among them, costs of cultivation (e.g. liquid culture must be constantly mixed), harvesting and infrastructure are the most important because they represent the bottleneck steps that still obstacle the economically viable production of microagal biomass, overall for energetic purposes [4]. Nowadays, the energy need is mainly satisfied by not renewable conventional sources, such as fossil fuels, carbon, petroleum and natural gas, which are responsible for greenhouse gas emissions (GHG). In this scenario, biomass represents a clean, renewable, programmable and large-scale available source for energy production. Moreover biomass is a carbon-neutral resource, since the carbon dioxide emitted can be efficiently absorbed by the photosynthesis cycle, achieving near zero balance of CO₂. In order to overcome alternative energy and environment challenges, improvement and intensification of microalgae culture can be proper strategies. Several advantages can be found if microalgae are used for energy purposes with respect to other renewable competitors. However, the capacity of microalgae to produce lipids (oil), fundamental for producing biofuels, and the ability to convert oil to biodiesel still need to be improved.

2. Improving microalgae cultivation

Attempts to improve microalgae biomass productivity and collection impacted in the past the biology of these organisms, by operating on their genetics, but also biotechnological engendering as well as the design of energy efficient systems to isolate/extract microalgae cells from water (concentration of microalgae cells with the actual technologies is in the order of mg/l) [3]. Microalgae cultivation requires specific environmental conditions including temperature, light intensity, mixing and gas exchange. Different species have slightly different requirements.

Currently, over 90% of world microalgae biomass production is realized in large raceway ponds (also known as racetrack) [5]. Other cultivation methods include closed bioreactor that may have different configuration: tubular, vertical column, flat panel and fermenter-type systems [6, 7]. Production of energy (biodiesel, bioethanol and syngas) from microalgae with this method is discouraged by initial capital investment and running cost which are the most critical drawbacks for an economically profitable production of biomass. The major criticism concern, as above mentioned, the costs for cultivation/harvesting and the cost of infrastructure. Other major disadvantages associated with open systems, partially determining the low productivity, are: I) land costs; II) contamination of culture by other algae, bacteria and/or other microorganisms; III) water evaporation as well as large volume of water; IV) difficulties to maintain an open algal culture during the rainy/winter season; V) energy waste for constant culture mixing; V) very low microalgae cell concentration in the liquid culture. The last drawback adds extra expenditure because large amount of water must be treated in order to concentrate microalgae biomass (see paragraph 3).

A recent cost-analysis study focused on open ponds, horizontal tubular and flat panel photobioreactors, showed that the costs of microalgae biomass production including dewatering, were 4.95, 4.15 and 5.96 €/kg, respectively [8]. The important cost factors considered were irradiation conditions, mixing, photosynthetic efficiency of systems, medium and carbon dioxide costs. Another study showed that the cost of photobioreactors is the major factor in the production cost [9]. In fact, if that could be reduced while maintaining the productivity, the production cost would decrease. Furthermore, the next factor in relevance is the consumption of raw materials. Carbon dioxide, that improves microalgae growth, is the most expensive consumable. A possible solution is to use flue gases from industrial sources which can reduce the cost of CO₂ to values as low as zero if flue gases are readily available. Moreover, the uptake of water and biomass harvesting also contributes
significantly to the production cost. Accordingly, it has been estimated that by optimizing all the above-mentioned parameters, the unit production cost can be reduced for tubular or flat panel photobioreactors to 0.70 and 0.68 €/kg, respectively, whereas for open raceways the cost cannot be reduced below 1.28 €/kg. Finally, it is now clear that the future of microalgae production relies on closed bioreactor. In particular, flat panel seems to offer the best cost/production ratio both in prospective studies and in current state-of-the-art production plant [10].

3. Improving microalgae harvesting

An optimal harvesting technique should be independent of the cultured species, consume little energy and few chemicals and not damage the valuable products in the extraction process. Traditional harvesting method may involve up to two steps: I) bulk harvesting (known as primary harvesting), to separate microalgae from suspension, such as sedimentation, flocculation, and flotation; and II) thickening (known as secondary dewatering), to concentrate the microalgae slurry after bulk harvesting, such as centrifugation and filtration. The microalgae recovery techniques represent between 20–30% of total production costs, so several other methods are exploited such as, magnetic separation, electrolysis, ultrasound and immobilization [5]. The major drawbacks in microalgae recovery are represented by the small size of microalgal cell (5–10 μm) and by their concentration in the liquid culture (mg/l) as well as cell-density (similar to water) and the negatively charged cell-surface that do not allow precipitation by gravity. Since the cell-size, density and electric potential are fixed parameters, ideally new harvesting methods should impact the concentration of microalgae cells in the liquid medium.

This can be achieved by enhancing the growth ratio of microalgae cells, and/or reducing the amount of water needed for their growth and by improving separation of microalgae cells from water. For the last point, engineering solutions that will allow to design new bioreactors which need minimum volume of water to growth microalgae and provide best cell-density detection are highly desirable. In fact, for example, by using sensors able to detect microalgae aggregations [11] will allow to collected them at the best concentration, optimizing energy feeding. In this way, the amount of energy used to separate microalgal biomass from water might be reduced. Furthermore, to improve microalgae harvesting great attention is put in the use of nanotechnologies. Ongoing research are exploring the biotechnological use of magnetic nanoparticles for microalgae cells harvesting with promising results [12]. In fact, thanks to their properties, functionalized nanoparticles are very promising for applications in bio-separation [13].

4. Improving transformation of microalgae in bio-fuels

Biofuel production from microalgae, biodiesel in particular, has a GHG emission up to 50 times lower than that from other unconventional sources such as palm oil, colza and soya [14, 15] but its production cost is higher than conventional diesel, in part due to the above-mentioned drawbacks. In the bioenergy sector microalgae could also be used for biogas/bio-methane production thanks to the simplicity of technology and the absence of lignin that is difficult to ferment, as it happens for various organic matter [16]. Same microalgae used for bioenergy applications are: *Botryococcus braunii*: green microalgae with high hydrocarbon content up to 80 wt.% of dry matter and able to grow in brackish waters but with slow growth rate as a disadvantage; *Chlorella*: it has an oil content in the range of 25-32 wt.% but in some cases could achieve 85 wt.% as for Chlorella pyrenoidosa and C. protothecoides.; *Dunaliella*: similar to Botryococcus braunii, it is a green microalgae that is able to grow in a high salt content environment. It has up to 23% of lipid content and is used in large scale plants for carotenoid production.

Several methods to extracted biofuels from microalgae have been proposed and are under intense investigation. These are: micro-emulsion of oils, pyrolysis and catalytic cracking, transesterification, thermo-chemical conversion and biochemical conversion [17]. An ideal method to convert microalgal biomass into biofuels should be a cost-effective technology, guarantee high efficiency conversion, environmental safe and most important easy to scale up for industrial applications. Among the
technologies used, Super Critical Water Gasification (SCWG), a thermo-chemical conversion technique, may offer the best opportunity. The advantage of this process is that it does not require drying of the high water containing microalgal biomass, which saves a lot of energy that other wise would have been used for drying purpose; is an environmental friendly process. In fact, water is heated above its critical temperature and pressure, and behaves as a very good solvent that completely dissolves and breaks the organic fraction of biomass. So, little or even no solvent is used and there is no generation of burn pollution. The output of this method is a mix of gases, (H/CH/CO,) named syngas, that can be directly burned to produce energy, used as a fuel to run diesel or gas turbine engines as well as separated into pure gases and used for transport, domestic heating and others purpose. Studies showed that the SCWG reaction can be energetically sustained if a minimum biomass concentration in the feed of 15–25% is adopted [18] and that microalgal biomass can reach 97.4% of gasification efficiency [19].

5. Conclusion

Multiple products extraction from microalgal biomass and integrated biorefineries, where it is possible to recover aqueous residual and CO₂, for example, could be fundamental for the development of new strategies to produce green energy and other high-value outputs with competitive costs. It is unlike that microalgae biomass production processes will be developed for, e.g., biofuels as the sole end-production. This synergetic strategy based on coupling different production processes can be the key to deal with the running cost of advanced biorefineries. In fact, in the first step of transformation from microalgal biomass could be extracted high-value natural compounds (dyes, essential oil and cosmetic molecules) and then used the vast majority of biomass (leftover) to biofuels production. On the other hand, improvement in microalgal cultivation, harvesting and transformation techniques that lower the operative cost are highly desirable in order to make microalgal biomass a competitive source of green energy.

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