Renewable and Sustainable Energy Reviews 81 (2018) 643–654

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

New insights into algae factories of the future

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ARTICLE INFO

Keywords:
CO_2 capture
Algal biomass
Flue gases
Carbon capture
Biofuels
Green transport

ABSTRACT

The total combined weight of biological material on planet Earth has been estimated in one source at about 75 × 10^9 t. Of this: crops comprise 2 × 10^9 t (2.7%) as well as microbes, fungi, algae and similar types of microorganisms are estimated to comprise over 50% of the total amount. Microalgae is outstanding among all the types of biomass sources in its ability to respond to the challenges of the future in terms of availability, high growth and production rates, yield per unit area, not competing for arable land, being most suitable optimal sources for both liquid and gaseous biofuels and valuable co-products within biorefineries. It is logical that the increased ability to occupy new niches in the energy sector is determined by uptake of the new forms of biomass exploitation coupled with environmental impact reduction. This could explain the worldwide interest in exploiting algal biomass as an ideal attribute for photosynthetic capture of anthropogenic carbon that reached a record high of ~ 10 Pg C yr^{-1} in 2014. In this review, we outline microalgae's potential to capture carbon in coal-fired power plant, discuss the advantages of photosynthetic organisms as a source for biodiesel and solid biofuel production, discuss the process engineering, different synergies and legislative factors needed to make the process efficient and economically viable. Before commercial-scale installations become feasible, however, numerous points still have to be resolved. In order to identify potentials and obtain recommendations for action, co-authors have studied in detail various options for climate-beneficial recycling and trapping CO_2 in the algae factories of the future that potentially could be built in the European humid continental climate countries.

1. Introduction

Historically microalgae have been of interest since 1942 [1,2] when Harder and von Witsch [3,4] proposed them as a source of vegetable oils. Even before that date, the relationship between nitrogen nutrition and lipid content of algae was already recognized [1]. After the World War II the study of microalgae lipids was pursued by groups in the United States [5], England [6], and Germany [7]. One of the first reports on biofuel processed from the lipids of *Chaetoceros muelleri* is dated 1990 [8]. Up till now algal biomass exhibits a range of uncertainties, overflows, speculative dimensions, and above all mixed modes of existence [9–16]. However, algal bio-crude is widely accepted these days by many researchers as a future source of biofuel worldwide [10,14,17–20].

Liquid, solid and gaseous biofuels from algae may become commercially available in the years 2020–2025 at the earliest, as the emerging algae-to-fuel systems has not been accomplished yet. There are various factors prompting application of algae-based fuels worldwide. The primary factor is limited petroleum resources predicted to last for about another 50 years. The European Union member countries alone consume approximately the fourth of the petroleum exploited globally per year. Global consumption of petroleum products has been growing as a result of rapid development of Asian economies (China, India) as well. EU authorities have recently started referring to new pollution and climate change control measures more frequently. There is unanimous consensus within the Community on securing long-term clean energy supplies for Europe in addition to the reduction of greenhouse gas emission from the energy and transport sectors [21].

Table 1 represents algae as universal product which can be used in many cases: food industry, pharmacy, farming, environmental, oil, and biofuel. European commission web page (http://cordis.europa.eu) was used for the survey. Around 400 projects were overviewed and some of them are listed in the Table 1.

Table 2 shows that algae as the fuel source has some negative factors which give impact for the high price, small payback, and low popularity. These factors led to the collapse of most of the projects. Expensive production and extraction processes determine high price of an end-product, while production payback depends on algae species,

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http://dx.doi.org/10.1016/j.rser.2017.08.024
Received 5 September 2016; Received in revised form 28 May 2017; Accepted 10 August 2017

Table 1
Survey on the state of algae related research.

Programme (Year)	Project	Research
ENV-LIFE 2 (1997–1999)	Demonstration plant of recycling for vegetable wastes and algae [22]	Composting plant where algae are used for the high quality organic product to be used for the farming.
IC-AVICENNE (1995–1998)	Use of wastewater for irrigation – a global approach blending water treatment, irrigation with various systems on various crops and institutional/organizational aspects [23]	Algae usage for heavy metal reduction in wastewater.
FP1 (1985–1986)	Production of liquid hydrocarbons from autotrophic biomass by low temperature autocatalytic conversion [24]	Biomass can be converted to oil relatively at low temperatures (250–380 °C). Such oil can be used as fuel source for transport or energy sectors. For example, biomass from algae are particularly suitable for this conversion method. Oil is extracted from 60% of organic carbon while approximately 30% of organic carbon becomes coal. More than 65% of net energy return is obtained using low temperature conversion method.
FP1 (1985–1987)	Optimization and metabolic control of the production of autotrophic microbial biomass [25]	Tubular photobioreactor was constructed for algal biomass production. Microcomputer was involved to keep required temperature and pH level. The main goal was to achieve biomass rich in lipids growing under the London climate conditions. For the research *Spirulina platensis* (microalgae species) was used with reduced quantity of light. It has been proven that even under that conditions algae biomass can be grown successfully.
FP1 (1986–1987)	Production of liquid hydrocarbons from autotrophic microbial biomass by low temperature autocatalytic conversion. Part 3: harvesting procedures of microalgae in seawater [26]	Biomass conversion to oil needs oily and fast growing cultures, especially for large scale oil production. Microalgae is one of the most promising culture which can be harvested using flocculation process. Harvesting procedure has high importance for further processes, whereas flocculation is simple and reliable. This technique is also economically acceptable (5–10 US cents per kg of oil).
FP1 (1988–1992)	Technology of high rate algal ponds for the photosynthetic reclamation of waste waters [27]	Improvement of algae ponds is required for a better efficiency treating waste water. Efficiency will be improved taking into account parameters such as pH, temperature, algae type, redox potential, dissolved oxygen, redox potential, bacterial strains.
FP4 (1996–1998)	Production of polyunsatured fatty acids (PUFAs) by algae: a complete bioprocessing concept for the large-scale production of high quality DHA-containing oils [28]	Production of polyunsaturated fatty acids and docosahexaenoic acid, containing oil, which can be used later for infant food or pharmaceutical purposes.
FP5 (2000–2001)	Hydroacustic tools for rapid industrial interest algae location [29]	Hydroacoustics prototype is able to find algae concentration places. Useful for searching of algae in natural places including harvesting as additional aspect.
FP7 (2009–2013)	Marine algae as biomass for biofuels [30]	*Dictyota* species from Mediterranean Sea was the oiliest 8.01% dry wt. basis, found in Turkey. *Bifurcaria bifurcata* species from Bantry Bay had oil content of 5.9% dry wt. basis, found in Ireland. Other microalgae species were grown in photobioreactors: with highest oil content was *Nannochloropsis oculata* 20.83% dry wt. basis.
FP7 (2010–2011)	Algae and aquatic biomass for a sustainable production of 2nd generation biofuels [31]	It was found that biomass, biodiesel and bioethanol can be produced from 72 species of algae. 30 of them were produced commercially and 47 species had potential to be cultivated in seawater.
FP7 (2010–2013)	Fuel making algae (Real-time non-invasive characterization and selection of oil-producing microalgae at the single-cell level) [32]	Not all algae species are suitable for the biofuel production. Iodine is one or the factor which shows the quantity of saturation of its fatty acids. Increment in lipid production using this technology can be achieved.
FP7 (2010–2015)	Biowaste and algae knowledge for the production of 2nd generation biofuels [33]	The BioWALK4Biofuels Project aims to develop an alternative and innovative system for the treatment of biowaste and use of GHG emissions to produce biofuels, using macroalgae as a catalyser, in a multidisciplinary approach [33].
FP7 (2011–2015)	Demonstration of integrated and sustainable enclosed raceway and photobioreactor microalgae cultivation with biodiesel production and validation [34]	Biofuel production from algae on industrial scale. It has to meet European Commissions (EC) 20:20:20 objectives. Cultivated algae production is going to be around 90–120 dry tons per hectare by annum. Algae species and harvesting method must be selected responsibly in order to meet biodiesel specifications.
FP7 (2011–2015)	BIOfuel from algae technologies. [35]	BIOFAT is a project with 10 ha of microalgae prepared for cultivation with annual productivity of 100 t/ha. Low energy centrifugation is used for biomass harvesting, mechanical cell disruption is made for extraction and finally biodiesel is made from oil by transesterification.
FP7 (2011–2016)	All gas (Industrial scale demonstration of sustainable algae cultures for biofuel production) [36]	Biofuel production on large scale using low-cost microalgae species. Project includes growing of algae, harvesting, production of biofuel and usage in the vehicles. Algae yield is going to be around 200 t per hectare per year and 20% of net oil content. Biogas will be produced from residues of algae. Wastewater will be used for the growth stimulation of algae and biogas production.
FP7 (2012–2017)	DEMA – Direct Ethanol from MicroAlgae [37]	Production of ethanol from microalgae using low cost bioreactors. Make it cheaper than from fossil fuel is the goal.
Horizon2020 (2016–2021)	Solenalgae. Improving photosynthetic solar energy conversion in microalgal cultures for the production of biofuels and high value products [38]	Only 45% of sunlight can be used for the photosynthesis. Microalgae can achieve maximum 10% of sunlight for the photosynthesis. Even worse number can be achieved around 1–3% if low light conditions are evaluated.

growing method, conditions, extraction method and many other factors including state approach and support. We found that crude oil has played significant role for the presented activities: at the moment of projects implementation the price of oil has reached lows and remained the most popular energy source in the investigated period of time. Of course, there is one key element which limits domination of crude oil in