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## Abstract

**Purpose** – Currently, experimental and theoretical work is being performed to ensure that biofuels from microalgae become a reality. However, there is a considerable number of discussions concerning in which processes should be focussed efforts of research and development. The purpose of this paper is to provide decision support not only to help build guidelines of research to be undertaken, but also to contribute to the design of more adequate policy and funding instruments. The key objective of this study is to determine the prospects of employing microalgae into the production of biofuels within a time scale extending to 2030.
**Design/methodology/approach** – The Delphi method is a qualitative research aiming to support strategic future-oriented action, such as policy making in the areas of science and technology. It is especially appropriate in judgment and long-range forecasting (20-30 years) situations, when expert opinions are often the only source of information available, due to a lack of appropriate historical, economic or technical data.
**Findings** – The Delphi method proved to be a successful research method when expert opinions are the main source of information available, due to a lack of appropriate historical, economic or technical data and the outcomes provided a clear outline of the main issues of microalgae biofuels' market at present and in the future.
**Research limitations/implications** – The outcomes might not represent the majority of the microalgae experts' opinion due to the sample size.
**Originality/value** – The work presented in this paper is especially original. According to the authors' knowledge, this is the first qualitative Delphi study related to algae biofuels.

**Keywords** Qualitative, Delphi, Energy, Renewables, Biofuels, Microalgae
**Paper type** Research paper

## 1. Introduction

Advanced biofuels such as the ones from microalgae are believed to be a better choice for achieving the goals of incorporating non-food based biofuels into the market. Extensive reviews dealing with several aspects of microalgae cultivation as feedstock

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for biofuel production are available in the literature (Williams and Laurens, 2010; Demirbas and Demirbas, 2010; Tao and Aden, 2009; Chisti, 2007, 2013; Brennan and Owende, 2010; Hirano *et al.*, 1997; Ono and Cuello, 2006; Pulz, 2001; Pulz and Gross, 2004; Sheehan *et al.*, 1998; Spolaore *et al.*, 2006; Terry and Raymond, 1985; Ugwu *et al.*, 2008; Delrue *et al.*, 2012; Wijffels and Barbosa, 2010). Currently, experimental and theoretical work is being performed to ensure that biofuels from microalgae become a reality, but there are a considerable number of discussions concerning which processes should be focussed efforts of research and development. To fill this gap, and building on previous work by the authors (Silva and Ribeiro, 2012; Ribeiro and Silva, 2012, 2013), this paper presents a study based on the Delphi method that it is aimed to provide decision support not only to help build guidelines of research to be undertaken, but also to contribute to the design of more adequate policy and funding instruments.

Due to the divergence and lack of appropriate historical, economic or technical data regarding some aspects of using microalgae as a feedstock for biofuels, a qualitative method, as presented in this paper, is especially appropriate for a long-range forecasting situation, when expert opinions are often the only source of information available.

This paper is structured as follows. In the next section, we present an overview of the European Union (EU) and US biofuel policies. In Section 3, a review of algae biofuel technology is provided with a brief comparison of biofuel feedstocks. The methodology of this study is presented in Section 4 with the results shown in Section 5. Finally, conclusions are drawn.

## 2. Biofuels governance context

In order to promote the use of energy from renewable sources, the European Parliament published on April 2009 the Directive 2009/28/EC which includes a policy target for the transport sector for every Member-State of 10 percent overall for the share of energy from renewable sources in 2020.

Currently, EU Member-States have to submit their national renewable energy action plans that outline how they intend to meet this target. Biodiesel and bioethanol/bio-ETBE are expected to have the largest share (more than 85 percent) of the renewable energy in transport in 2020, followed by other types of biofuels and renewable electricity (Kampman *et al.*, 2013).

Large-scale implementation of these additional fuels may, however, require targeted policy measures, as well as new fuel and vehicle standards, adaptation of engines and fuel distribution, not to mention that consumers need to be aware of the new fuels (Kampman *et al.*, 2013).

Concerning the environmental sustainability of biofuels, the Directive 2009/28/EC establishes in its Article 17, the sustainability criteria for these fuels, stating that biofuels that do not fulfill the sustainability criteria set out in this article shall not be taken into account. The main criteria are:

- the greenhouse gas emission saving from the use of biofuels taken into account shall be at least 35 percent. From January 2017, the greenhouse gas emission saving shall be at least 50 percent and from January 2018 shall be at least 60 percent;
- biofuels shall not be made from raw material obtained from land with high biodiversity value;

- biofuels shall not be from land with high carbon stock; or
- biofuels shall not be from land that was peatland in January 2008, unless evidence is provided that the cultivation and harvesting of that raw material does not involve drainage of previously undrained soil.

By the end of 2010, a communication from the European Parliament has set the strategy for competitive, sustainable and secure energy by 2020. The Strategic Energy Technology (SET) Plan (Strategy Energy Technologies Information System, 2013) sets out a medium term strategy valid across all sectors. Yet, development and demonstration projects for the main technologies (e.g. second generation biofuels) must be sped up (EU, 2010).

In a similar approach of Europe, The US Environmental Protection Agency suggested revisions to the National Renewable Fuel Standard (RFS) Program. The proposed rules intended to address changes to the RFS program as required by the Energy Independence and Security Act (EISA) of 2007. The revised statutory requirements establish new specific volume standards for cellulosic biofuel, biomass-based diesel, advanced biofuel and total renewable fuel that must be used in transportation fuel each year. The regulatory requirements for RFS will apply to domestic and foreign producers and importers of renewable fuel (Renewable Fuel Standards (RFS), 2013a).

This rule proposed to establish the revised annual renewable fuel standard (RFS2), and to make the necessary program modifications as set forth in EISA. Therefore, EISA increased the volume of renewable fuel required to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022 (RFS, 2013b).

In addition, EISA established new categories of renewable fuel and required EPA to apply lifecycle greenhouse gas performance threshold standards to ensure that each category of renewable fuel emits fewer greenhouse gases than the petroleum fuel it replaces. RFS2 expects to achieve significant reductions of greenhouse gas emissions from the use of renewable fuels and from reducing petroleum imports (RFS, 2013a).

The proposed specific targets for 2014 in the USA include 17 million gallons from cellulosic biofuel, 1.28 billion gallons from biomass-related diesel, 2.2 billion gallons from advanced biofuel, adding to a total of 18.15 billion gallons of renewable fuels (considering corn-based ethanol). If algae-based fuels meet RFS greenhouse gas emissions requirements, they could be considered under the advanced biofuel or bio-based diesel portion of the RFS, according to the proposed rule. While cellulosic ethanol is expected to play a large role in meeting the 2007 EISA goals, a number of next generation biofuels, particularly those with higher energy density than ethanol, show significant promise in helping to achieve the 36 billion gallon goal (US Department of Energy, 2010).

Of these candidates, algal biofuels are generating substantial awareness in many countries. In the USA, they may contribute to achieve the biofuel production targets set by the energy independence and security act of 2007. Likewise, in the EU, they may assist to the achievement of goals established in the current renewables directive. In order to address the technical-economic barriers to the further development of this type of bio-energy, it revealed to be necessary to contribute with a study that incorporates biomass feedstock availability assessment, production, management and harvesting in support of the up-scaling of this promising technology, as is it in this chapter provided. In the next section algae biofuels will be presented and discussed.

## 3. Revisiting algae biofuels

### *3.1 Algae technical specificities*

Several studies have been conducted on the technical feasibility of growing algae for biofuel production in the laboratory (Williams and Laurens, 2010; Demirbas and Demirbas, 2010; Tao and Aden, 2009; Chisti, 2007; Brennan and Owende, 2010; Hirano *et al.*, 1997; Ono and Cuello, 2006; Pulz, 2001; Pulz and Gross, 2004; Sheehan *et al.*, 1998; Spolaore *et al.*, 2006; Terry and Raymond, 1985; Ugwu *et al.*, 2008; Delrue *et al.*, 2012; Wijffels and Barbosa, 2010), which have proved absence of the major drawbacks associated with current biofuels. However, several hurdles still need to be overcome in order to scale up the production, while the costs of producing this emerging biofuels are still high compared with other biofuel sources.

This technology uses the oils from microalgae as the raw material to produce biofuel. Microalgae are microscopic photosynthetic organisms that are found in both marine and freshwater. These organisms use solar energy to combine water with carbon dioxide ($CO_2$) to create biomass (Terry and Raymond, 1985).

The mechanism of photosynthesis in microalgae is similar to higher plants, with the difference that the conversion of solar energy is generally more efficient because of their simplified cellular structure and more efficient access to water, $CO_2$ and other nutrients. For these reasons, microalgae are capable of producing 30 times as much oil per unit of land area compared to terrestrial oilseed (Terry and Raymond, 1985).

Algae can be autotrophic or heterotrophic; the first requiring only inorganic compounds such as $CO_2$, salts and a source of light energy for their growth, while the latter are non-photosynthetic, therefore requiring an external source of organic compounds and nutrients as a source of energy (Brennan and Owende, 2010).

In microalgae cultivation, $CO_2$ must be fed constantly during daylight hours. Algae biodiesel production can potentially use some of the $CO_2$ that is released by some industries. This $CO_2$ is often available at little or no cost (Chisti, 2007). However, the fixation of the waste $CO_2$ of other sorts of business could represent another source of income to the algae industry. This sort of fixation is already being made in some large algae companies in a trial basis; though, there is a lack of public data of the results yet. Although this is a very promising future possibility, and some species have proven to show themselves capable of using the flue gas as nutrients, there are few species that survive at high concentrations of $NO_x$ and $SO_x$ present in these gases (Brown, 1996).

Ideally, microalgal biodiesel would be carbon neutral, as all the power needed for producing and processing the algae would come from biodiesel itself and from methane produced by anaerobic digestion of biomass residue left behind after the oils has been extracted. Although microalgal biodiesel can be carbon neutral, it will not result in any net reduction in $CO_2$ as a consequence of burning the produced fuels to generate energy (Chisti, 2007).

The nutrients for the cultivation of microalgae (mainly nitrogen and phosphorus) can be obtained from liquid effluent wastewater (sewer); therefore, besides providing its growth environment, there is the potential possibility of waste effluents treatment (Cantrell *et al.*, 2008). This could be explored by microalgae farms as a source of income in a way that they could provide the treatment of public wastewater, and obtain the nutrients the algae need.

After the process of extracting the oil from algae, the resulting product can be converted to biodiesel. The biodiesel produced from algal oil has physical and chemical properties similar to diesel from petroleum, to biodiesel produced from terrestrial crops and compares favorably with the International Biodiesel Standard for Vehicles (EN14214) (Brennan and Owende, 2010).

Like a refinery, it is still possible to obtain other products in the cultivation of microalgae, such as ethanol, methane and biohydrogen (Ferreira *et al.*, 2013). Although they are possible processes and proven in the laboratory, they were still little studied in industrial scale.

As of today, it has been shown that it is scientifically and technically possible to derive the desired energy products from algae in the laboratory. The question lies, however, in whether it is a technology that merits the support and development to overcome existing scalability challenges and make it economically feasible (Mcgraw, 2009). Economic viability is believed to be currently the main hurdle to overcome for this technology. Current costs associated to both the state of the science and technologies are sizeable and represent a main factor working against development.

Commercial algae production facilities employ both open and closed cultivation systems. Each of these has advantages and disadvantages, but both require high capital input. Closed photobioreactors are significantly more expensive to construct, but have not been engineered to the extent of other reactors in commercial practice, and so there may be opportunities for significant cost reductions. Neither open ponds nor closed photobioreactors are mature technologies. Therefore, until large-scale systems are built and operated over a number of years, many uncertainties will remain. Cultivation issues for both open and closed systems, such as reactor construction materials, mixing, optimal cultivation scale, heating/cooling, evaporation, $O_2$ build-up, and $CO_2$ administration, have been considered and explored to some degree, but more definitive answers await detailed and expansive scale-up evaluations (Pienkos and Darzins, 2009).

### *3.2 Comparing feedstocks for biofuel*

Biofuel production could be made from several sources. Among crops, it could be obtained from corn, sugar cane, switch grass, soybeans, rapeseed, canola, etc. Each crop has its own impacts and land-use requirements as stated in Table I. When the oil yield of different biofuel crops is compared, it becomes clearer that microalgae biofuels are far more efficient, as demonstrated by Chisti (2007).

### *3.3 Gains and shortcomings*

Contrasting to other sources of feedstock to produce biofuels, algae-based biofuels present several advantages. These advantages comprise:

- capability of producing oil during all year long, therefore the oil productivity of microalgae is greater compared to the most efficient crops;
- producing in brackish water and on not arable land (Searchinger *et al.*, 2008); not affecting food supply or the use of soil for other purposes (Chisti, 2007);
- possessing a fast growing potential and several species have 20 to 50 percent of oil content by weight of dry biomass (Chisti, 2007);
- regarding air quality, production of microalgae biomass can fix $CO_2$ (1 kg of algal biomass fixes roughly 1.83 kg of $CO_2$) (Chisti, 2007);
- nutrients for its cultivation (nitrogen and phosphorous, mainly) can be obtained from sewage, therefore there is a possibility to assist the municipal wastewater treatment (Cantrell *et al.*, 2008);

| Crop type | Used to produce | GHG Emissions[a] (Kg of $CO_2$ created per mega joule of energy produced) | Use of resources during growing, harvesting and refining of fuel Water | Fertilizer | Pesticide | Energy | Pros and Cons |
|---|---|---|---|---|---|---|---|
| Corn | Ethanol | 81-85 | High | High | High | High | Technology ready and relatively cheap; reduces food supply |
| Sugar cane | Ethanol | 4-12 | High | High | Med | Med | Technology ready; limited as to where it will grow; reduces food supply |
| Switch grass | Ethanol | −24 | Med-low | Low | Low | Low | It will not compete with food crops; technology not ready |
| Wood residue | Ethanol, biodiesel | N/A | Med | Low | Low | Low | Technology ready; reduces food supply |
| Soybeans | Biodiesel | 49 | High | Low-med | Med | Med-low | Technology ready; reduces food supply |
| Rapeseed, canola | Biodiesel | 37 | High | Med | Med | Med-low | Technology ready; reduces food supply |
| Algae | Biodiesel | −183 | Med | Low | Low | High | Potential for huge production levels; technology not fully ready for scale up |

**Notes:** [a]Emissions produced during the growing, harvesting, refining and burning. Gasoline is 94, diesel is 83
**Source:** Adapted from Groom *et al.* (2008)

**Table I.** Comparison of biofuel feedstock environmental impacts for transportation fuels



- growing algae do not require the use of herbicides or pesticides (Rodolfi *et al.*, 2009);
- algae can also produce valuable co-products, as proteins and biomass after oil extraction, that can be used as animal feed, medicines or fertilizers (Brennan and Owende, 2010; Spolaore *et al.*, 2006), or fermented to produce ethanol or methane (Hirano *et al.*, 1997);
- biochemical composition of algal biomass can be modulated by different growth conditions, so the oil yield can be significantly improved (Qin, 2005);
- capability of performing the photobiological production of "biohydrogen" (Ferreira *et al.*, 2013; Ghirardi *et al.*, 2000); and
- the possibility to produce aviation fuels can be a future role of algal biofuels (Norsker *et al.*, 2011).

The above combination of the potential for biofuel production, $CO_2$ fixation, wastewater treatment and the possibility of production of biohydrogen highlights the potential applications of the microalgae cultivation.

Although several production options are possible, the "ideal" microalgae cultivation and extraction processes are yet to be found. The endeavor to find a process that fulfils all the environmental, technical and economical needs presented so far is quite challenging, if ever to be found. Caution is required to access all the information regarding algae biofuels not to set barely unattainable goals based on several different assumptions (Klein-Marcuschamer, 2013).

Compared to other biofuel technologies, the most favorable factors for the cultivation of microalgae for the production of biofuels is that they can be grown in brackish (salt) water, on non-fertile land and the oil yield production is far superior.

Despite its vocation as a potential source of biofuels, many challenges have hindered the development of biofuels technology from microalgae to become commercially viable.

Among them, and based on recent literature, we elect as the most important:

- the selection of species must balance the requirements for biofuel production and extraction of valuable by-products (Ono and Cuello, 2006);
- achieve greater photosynthetic efficiency through the continuous development of production systems (Pulz and Scheinbenbogen, 1998);
- developing techniques for growing a single species, reducing evaporation losses and diffusion of $CO_2$ (Ugwu *et al.*, 2008);
- few commercial cultivating "farms", so there is a lack of data on large-scale cultivation (Pulz, 2001);
- impossibility of introducing flue gas at high concentrations, due to the presence of toxic compounds such as $NO_x$ and $SO_x$ (Cantrell *et al.*, 2008);
- choosing algae strains that require fresh water to grow can be unsustainable for operations on a large scale and exacerbate fresh water scarcity (Mcgraw, 2009);
- current harvest and dewatering are still too energy intensive (Chen *et al.*, 2009);
- some recent life cycle analyses project algae biofuels as having poor energy or greenhouse gas benefits (Benemann, 2012);
- another disappointment that will likely arise is the scarcity of sites with favorable climate, land, water and $CO_2$ resources, all required in one place (Moody *et al.*, 2014);
- a reliable and continued $CO_2$ supply source can be scarce depending on the region assessed (Middleton *et al.*, 2014);
- $CO_2$ supply is relatively expensive, due to high capital and operational costs for piping $CO_2$ to, and transferring it into, the ponds (Benemann, 2012); and
- the application of genetically modified algae may be inevitable in terms of overall feasibility, but does raise concerns relating to ecological impacts (Chisti, 2013).

Several technologies most critical need is to demonstrate efficiency at the appropriate scale – pilot plants, pre-commercial demonstration or full industrial scale. In the case of microalgae pilot plants have been deployed lately and some pre-commercial plants are being constructed. Therefore, due to a lack of appropriate economic and technical data, expert opinions are a key source of information in this market.

In the next section, the methodology of this work is presented with the aim to better define which lines of research could be supported, which policy and funding instruments are more suitable and what the experts' visions towards algae biofuels are.

## 4. Methodology

The Delphi method is a qualitative research aiming to support strategic future-oriented action, such as policy making in the areas of science and technology. It typically entails two or more survey rounds in which the participating experts are provided with the results of the previous rounds. The panel of experts is used as the source of information, and the questionnaires act as the medium of interaction. The key characteristics of a traditional Delphi study are iteration, participant and response anonymity, controlled feedback, and group statistical response. It is especially appropriate in judgment and long-range forecasting (20-30 years) situations, when expert opinions are often the only source of information available, due to a lack of appropriate historical, economic or technical data (Blind *et al.*, 2001; Mcleod and Childs, 2007; Rowe and Wright, 1999).

The key objective of our Delphi study is to determine the prospects of employing microalgae into the production of biofuels within a time scale extending to 2030. Before initiating the Delphi study, a brainstorming was organized by four microalgae specialists where the main factors that affect production and competition of microalgae biofuels were discussed and indentified. Subsequently, statements were written with the aim of presenting these factors to the future interviewees. These statements were then categorized in different themes and composed the First Delphi Survey Round. The questionnaires were sent to microalgae experts via e-mail, enquiring about their willingness to participate in the study. Those that accepted the invitation received a internet link with the survey.

Our Delphi study included three survey rounds (a workshop and two Delphi rounds), which made it possible to understand the features that may develop or hold back microalgae biofuels in the future. All three rounds were carried out during three months (from May 2012 to July 2012). There were 55 respondents in the first round, reaching a response rate of 36.7 percent, and, in the second round, when only were questioned those that answered the first round, the response rate was 54.5 percent. The Delphi participants were selected based on their expertise on the subject matter, as it was required in-depth knowledge about the microalgae biofuel markets and processes from all the experts.

Overall, the panelists represented ten countries (USA, Portugal, the Netherlands, Italy, Norway, UK, Spain, Uruguay, Brazil and Australia). The experts can be categorized into three groups based on the field they represented: Academy (38.5 percent), Government (23.1 percent), Business (28.8 percent), Academy/Business (7.7 percent) and Academy/Business/Government (1.9 percent). The main focus of this Delphi study was to gather insights from specialists that symbolized distinctive fields, and not specifically the strategies of each country.

The statements were categorized into four main themes. The first theme concerned microalgae biofuel economics as it plays a crucial role in establishing well-functioning and competitive market. The second theme studied some future trend hypothesis to be rejected or accepted by participants on the Delphi survey. The third key element in the study dealt with sustainability, which directly affects confidence-building in the development of the microalgae biofuel market. The final group of statements focused on policies and on forecast concerning the future.

The first round questionnaire consisted of 50 statements. Those that did not reach an overall consensus (more than 66 percent agree or disagree) shaped the basis of the second round, which included open-ended fields for further explanations or suggestions. The second round focussed on clarifying the answers of the first round.

All the questionnaires were pre-tested, and the panelists were given feedback after the first round with all the participants' answers from the first round. The full list with all the statements is presented as a complementary file of this paper.

## 5. Main outcomes

One of the key findings is that most of the experts believe that the production of microalgae for biofuels will achieve full commercial scale until 2020 and from that period on, it could represent an important share of the total worldwide fuel consumption, as shown in Figure 1. On the other hand, environmental issues are most likely to reveal divergent opinions from experts, conceivably because biofuels of this origin do not yet present a well-known industrial process and microalgae are not still being cultivated commercially for this purpose.

In order to boost development, experts agree that "public investment in R&D" is the most important policy to be adopted by countries. In this way, R&D investment, not only in the algae industry, but also in all advanced biofuels, can be crucial to the development of these technologies.

The other policies worth considering in the experts point of view were "Developing strategies aimed to renewable resources" and "tax incentives and subsidies". Setting "Sustainable Standards (emission, production, etc.)" were also encouraged as shown in Table II.

Moreover, with policy support and incentives, the algal biofuels industry (and advanced biofuels) will continue to develop and assuming that this technology follows renewable energy cost trends, costs will decrease to eventual economic

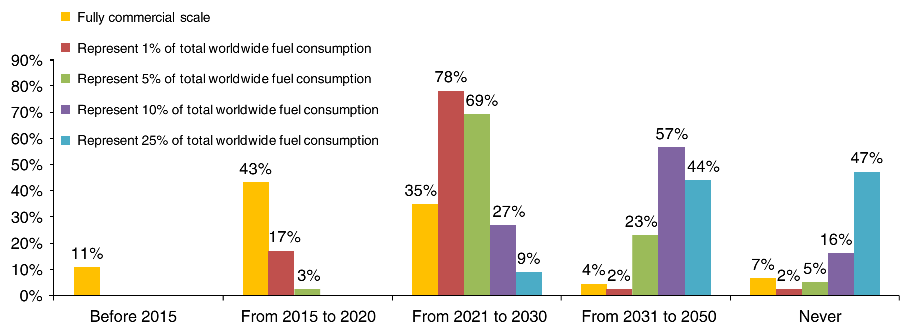


**Figure 1.** When do you think the following would happen in microalgae biofuels industry?

**Table II.** How important is each policy below to the success of microalgae biofuels?

| Policies | Mean |
|---|---|
| Public investment in R&D | 6.09 |
| Development strategies aimed to renewable resources, either research, utilization and integration in existing systems | 5.91 |
| Tax incentives and subsidies | 5.71 |
| Sustainability standards (Emissions, production, etc.) | 5.70 |
| Specific legislation or international agreements (such as European Directives) aimed specifically to biofuels or to specific environmental questions (such as carbon emissions) where biofuels have a pivotal role | 5.70 |
| Mandatory country objectives | 5.52 |
| Certification schemes, in particular those concerning raw materials or the entire fuel life cycle | 5.48 |

viability. On the other hand, if no public policy is enabled to enhance the Advanced Biofuels industry, it would probably play a minor role in the future of energy transportation. This scenario could dramatically change depending on the policies adopted.

Regarding algae biofuel economics, environmental sustainability and future trends, some statements demonstrated very high level of agreement among the experts (above 90 percent), as mentioned in the list below.

Statements that demonstrated very high level of agreement among the experts (above 90 percent):

- Statement 1: "Achieving economic viability is considered one of the main challenges facing large-scale deployment of biofuels from micro-algae."
- Statement 2: "The potential of using waste streams from other processes, industries or systems, as for example waste flue gases or waste waters, can have a significant impact in the microalgae economic process viability."
- Statement 3: "There is still plenty of room for innovative and more effective production processes, from the cultivation, passing through the raw material processing, chemical reactions involved and purification steps."
- Statement 4: "Different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions. No single strain will be dominant one."

The Statements from the Economics category that reached a high level of consensus point out the expectation of experts about the economical feasibility of algae biofuels. Most of them think this is considered one of the main challenges facing large-scale deployment of biofuels from microalgae (Statement 1). In order to reach this wanted economical balance, Statements 2 and 3 prove that, in the view of the vast majority of experts, there is plenty of room for innovative and more effective production processes that could lead to processes improvements, and thereafter, to economical profits.

The remaining statement that reached very high consensus was regarding the strains to be used in future algae biofuel cultivations. The experts believe that no single strain will be dominant one, and depending on local nutrients, waste streams, climatic and water availability the strains that are more suitable to each location would be selected.

Some other statements reached consensus with lower agreement compared to the previous items (above 80 percent agree, but less than 90 percent) but still with a high level of consensus, as shown in in the list below.

Statements that demonstrated high level of agreement among the experts (from 80 to 90 percent):

- Statement 5: "R&D subsidies and support programmes will be needed to promote improvements in the technology that reduce the costs of algal biofuels."
- Statement 6: "One of the key advantages of cultivating microalgae is the capacity of producing raw materials all year round, simplifying the process logistics and reducing costs."
- Statement 7: "The economic feasibility is strongly affected by the amount of energy needed in the process, mainly due to the high water content of the original raw materials that has to be removed before the chemical reaction."

- Statement 8: "The increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae."
- Statement 9: "Microalgae cultivation may become an important factor in the development of local economies and reduce the dependence on non-renewable energy sources."
- Statement 10: "Biofuels from microalgae will be produced commercially, but only in the mid to long term."
- Statement 11: "The main aspects that have to be considered in the process development are improving its overall energy efficiency, the ability to produce other high value products, or the possibility to integrate it in other process under the biorefinery concept umbrella."
- Statement 12: "The reduction in the dependence in oil imports, and the potential development of local and national economies is a relevant factor in the development of the area."
- Statement 13: "The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability."

Statements 6, 7, 11 and 13 are strongly related to the cultivation processes and present key factors that could enhance the overall feasibility of algae biofuels if tackled with success. These statements presented a high level of agreement among the algae experts. Some of these issues were already pointed out by other authors such as Chisti (2007), Benemann (2012) and Brennan and Owende (2010).

The other statements of this group of moderate agreement comprise economy related topics. From those, it is important to highlight that the majority of experts think that R&D subsidies and support programmes will be necessary so that algae biofuels become competitive with other sources of fuels. As recognized by Popp *et al.* (2001), the higher costs of renewable energy technologies urge policy intervention to encourage investment. Otherwise, in the lack of public policy favoring the development of renewable energy, production costs remain too high and they cannot represent an option in replacing fossil fuels.

The next statements (in the list below) were those that reached a moderate consensus (above 66 percent agree) but have not surpassed the 80 percent agreement mark.

Statements that demonstrated moderate level of agreement among the experts (from 66 to 80 percent):

- Statement 14: "The idea of a Biorefinery is considered the business model more likely to ensure the economic viability of microalgae cultivation for biofuel production."
- Statement 15: "Besides biofuels, the more relevant co products that will improve the economic viability of microalgae cultivation are nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries."
- Statement 16: "The utilization of Genetic Engineering or more effective selection criteria may lead to more effective strains of microalgae, in particular in terms of overall productivity and/or cultivation robustness."

- Statement 17: "The limiting steps, in terms or processing costs, are the oil separation and water removal steps. Any improvements in these steps can have a profound impact in the economical feasibility of the microalgae biofuel production process."
- Statement 18: "The economical viability of the microalgae production can be further enhanced if biofuels applications outside the transportation sector can be found and promoted."
- Statement 19: "Higher petro oil prices could make algae biofuel economically feasible."
- Statement 20: "A more developed, globalized and comprehensive Carbon Market could make algae biofuel more economically feasible."
- Statement 21: "Advances in strain identification and process engineering are key factors in the development of the technology."
- Statement 22: "The nature of the cultivation system, closed or open, will depend on the production quantities, type of nutrients required, waste streams available and strains used."
- Statement 23: "The microalgae cultivation process will be increasingly used integrated in existing industrial processes, usually not related with energy production and for waste treatment and/or carbon capture purposes."
- Statement 24: "The need to reduce world's $CO_2$ emissions is a key advantage for algae biofuels."
- Statement 25: "Although microalgae can be used to capture $CO_2$, the actual overall life cycle carbon balance is key aspect to consider."
- Statement 26: "The potential of biofuels from microalgae to be carbon neutral is a key factor concerning their sustainability."

In the statements described in the list above, several different topics are covered. First, some issues concerning cultivating processes are discussed, in which it is possible to highlight the idea of biorefinery as the business model to be used and the possibility to use genetically modified organisms to enhance the productivity and/or the cultivation. Genetically modified organisms may present an opportunity to increase feasibility of algae biofuels but at the same time can present a threat to its acceptability and, therefore, penetration in the market due to sustainability issues (Mcgraw, 2009; Chisti, 2013).

Regarding environmental sustainability, a key aspect found in this section concerns about $CO_2$ emissions and capture. Experts agree that the necessity to reduce world's $CO_2$ emissions is a key advantage for algae biofuels, and although the actual overall life cycle carbon balance is still under harsh debate (Lardon *et al.*, 2009; Clarens *et al.*, 2010; Collet *et al.*, 2011; Liu *et al.*, 2013; Sander and Murthy, 2010), they consider biofuels from microalgae to be carbon neutral a key factor concerning their sustainability.

Another aspect concerning sustainability regards to energy use. The Net Energy Ratio of algae biofuels normally performs poorly when compared to petrol fuels, although some innovative processes claim they can improve it greatly, it still is an area of vast debate (Batan *et al.*, 2010; Lardon *et al.*, 2009; Frank *et al.*, 2012; Sander and Murthy, 2010; Delrue *et al.*, 2012, 2013).

Lastly, economical matters are discussed pointing that experts believe that future higher petro oil prices could make algae feedstock for biofuels an economically feasible one, as already explored by Chisti (2007, 2013). They also believe that a more developed Carbon Market could affect positively algae biofuel markets, enhancing economical feasibility.

Once all the respondents had completed the first round, the statements that did not reach an overall consensus were asked once more on the second round. Some of these statements are presented as follows.

Statement 27: "Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated."

This statement has a clear tendency on agreement (63.6 percent agree), however, we could not conclude on a clear overall consensus and some of the experts expressed their opinions for and against it. Some of the experts' answers are presented as follows and could lead to an understanding why this statement did not achieve a consensus:

> High-value products may be co-products of any successfully large-scale biofuel production from algae, but co-products may not be possible at the scale of biofuels, which will be huge (Strongly Disagree).

> This is akin to a petrochemical complex, generates less residues, and ensures that there is a lower risk in the microalgae base industry as there is less dependence on just one product (Strongly Agree).

> Depends on the commercialization strategy of the facility; a near-term, "1st of a kind" facility may rely primarily on other high-value products to generate required revenue with algal oil/biofuel as a co-product, and could transition to a larger emphasis on algal biofuel as a principal product as the technology matures (Neither Agree nor Disagree).

Statement 28: "Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector."

Since this prediction involves several factors, it was difficult for experts to reach a consensus (47.1 percent agree/25.5 percent neither agree nor disagree/27.5 percent disagree):

> Algal biofuels have the potential to play a major role in the future mix relative to many other biofuel pathways, but it depends on cost and time scale (Disagree).

> Too early to reach conclusions (Neither Agree nor Disagree).

Statement 29: "The environmental sustainability of microalgal derived biofuels is a potential problem."

Since microalgae biofuels do not have a well-known industrial process (there are different methods for producing them) and microalgae are not yet being cultivated commercially for this purpose, it was difficult for the experts to answer questions related to environmental sustainability of this innovative technology. As exposed before, some studies presenting Life Cycle Assessments (LCAs) of algae biofuels are conflicting (Lardon *et al.*, 2009; Clarens *et al.*, 2010; Collet *et al.*, 2011; Liu *et al.*, 2013). Therefore no agreement was reached in this statement (38 percent agree/28 percent neither agree nor disagree/ 34 percent disagree). Some of the experts' answers are shown as follows:

> In the near term, Life-Cycle Assessment (LCA) is challenging, but can be overcome with process and biology improvements (Disagree).

Only if actions to minimize/restrict those impacts are not taken (Agree).

There is not sufficient evidence in the literature to support or negate this statement (Neither Agree nor Disagree).

## 6. Final considerations

It is increasingly clearer to society that the continued use of fossil fuels for energetic purposes is unsustainable. Therefore, other sources of energy must be developed to replace fossil fuels. Alternative sources derived from terrestrial crops such as sugarcane, soybeans, maize, and rape seed, among others, inflict a lot of pressure on the global food markets, contribute to water scarcity and precipitate the destruction of forests. Besides that, many countries cannot grow most of the terrestrial crops due to climate factors or lack of fertile cultivation areas for energetic purposes.

The focus of using renewable energy in the transport sector leads to reduced dependence on oil, and consequently a reduction in the external trade deficit balance. Also results in a reduction of $CO_2$ emissions thereby contributing to tackle climate change by reducing greenhouse gases emissions. Moreover, diversification of supply sources leads to more security of supply, essential for the transport sector by the endogenous production of fuels that leads to greater control of its production and introduction into the market.

This is where the algal biofuels can really make a contribution for the future world sustainability, since most studies confirmed the technical and biological feasibility to produce biofuels in large quantities from microalgae. However, Environmental sustainability can be directly affected by several issues in microalgae cultivation, such as poor energy balance, water scarcity or greenhouse gas benefits if some processes are not adopted in the cultivation and production. Some of the key processes are anaerobic digestion to generate energy for the process, recycling nutrients from wastewater and seawater, and using a source of $CO_2$ from emitting industries. The need of finding locations with favorable climate, in non-agricultural land, with feasible water supply and $CO_2$ resources are also key aspects concerning environmental sustainability of microalgae biofuels.

Social equity presents a favorable panorama. The possibility to produce fuels with no need of "proven geographical reserves" renders to this technology a strong social characteristic, in which many countries have the possibility to produce it. This allows increased independence on foreign energy and increase the energy security of producing countries, as developing domestic sources of energy are key to promoting energy security. Moreover, for developing countries with high levels of poverty, the relationship of increased consumption of energy and well-being is stronger. Therefore, beyond job generation impacts, providing economic stimulus for such countries, algal biofuel production would provide energy availability and security, while encouraging infrastructure and social development, without the dire effects of the food versus fuel issue of first generation biofuels.

Economical viability still is uncertain as the cost of producing biofuels from algae still generates divergence among experts and it is unknown, so far, if it could compete equally with other fuels in the market. Thus, for the establishment of a credible market, steady and with a growing demand, experts agree that microalgae biofuels need to be stimulated, as many of the implementation stages of emerging technologies can face limitations that can lower the possibility of success. Therefore, with policy support and incentives, the algal biofuel industry could continue to develop and assuming that this technology follows renewable energy cost trends, costs would decrease to eventually reach economic viability.

The Delphi method proved to be a successful research method when expert opinions are the main source of information available, due to a lack of appropriate historical, economic or technical data and the outcomes herein, provided a clear outline of the main issues of microalgae biofuels' market at present and in the future. In particular, the two-round survey revealed the most important issues affecting this emerging market and also, recommended ways to influence future policies and development of this biofuel, in a field where policy frameworks have to be addressed in order to develop the market penetration of such emerging technology.

Although this research has reached its aims, some challenges ahead still remain. First of all, the sample size could have been bigger and thus, more representative in statistical terms. The authors of this chapter are aware that the outcomes might not represent the majority of the microalgae experts' opinion. In the same manner, after analyzing the results, some questions did not reach a consensus and could be further explored in a supplementary study or in a third round.



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(The Appendix follows overleaf.)

## Appendix

| Stat. | *Theme 1: economics* |
|---|---|
| 1.1 | Achieving economic viability is considered one of the main challenges facing large-scale deployment of biofuels from microalgae |
| 1.2 | The idea of a biorefinery is considered the business model more likely to ensure the economic viability of microalgae cultivation for biofuel production |
| 1.3 | Microalgae biofuel will become a co-product of future large-scale facilities, where other high-value products are generated |
| 1.4 | The price of competing fuels, especially biobased, will make it difficult for algal biofuels to achieve high growth on the cost only basis |
| 1.5 | R&D subsidies and support programmes will be needed to promote improvements in the technology that reduce the costs of algal biofuels |
| 1.6 | The potential of using waste streams from other processes, industries or systems, as for example waste flue gases or waste waters, can have a significant impact in the microalgae economic process viability |
| 1.7 | Besides biofuels, the more relevant co products that will improve the economic viability of microalgae cultivation are nutraceuticals and compounds for the pharmaceutical and/or fine chemistry industries |
| 1.8 | One of the key advantages of cultivating microalgae is the capacity of producing raw materials all year round, simplifying the process logistics and reducing costs |
| 1.9 | The utilization of genetic engineering or more effective selection criteria may lead to more effective strains of microalgae, in particular in terms of overall productivity and/or cultivation robustness |
| 1.10 | The economic feasibility is strongly affected by the amount of energy needed in the process, mainly due to the high water content of the original raw materials that has to be removed before the chemical reaction |
| 1.11 | The limiting steps, in terms or processing costs, are the oil separation and water removal steps. Any improvements in these steps can have a profound impact in the economic feasibility of the microalgae biofuel production process |
| 1.12 | There is still plenty of room for innovative and more effective production processes, from the cultivation, passing through the raw material processing, chemical reactions involved and purification steps |
| 1.13 | The increase in the overall consumption of biofuels, and the expected growing pressures on currently used feedstocks can be a key factor to the economic viability of microalgae |
| 1.14 | The economic viability of the microalgae production can be further enhanced if biofuels applications outside the transportation sector can be found and promoted |
| 1.15 | Microalgae cultivation may become an important factor in the development of local economies and reduce the dependence on non-renewable energy sources |
| | *Theme 2: future trends* |
| 2.1 | Higher petro oil prices could make algae biofuel economically feasible |
| 2.2 | A more developed, globalized and comprehensive carbon market could make algae biofuel more economically feasible |
| 2.3 | Algal biofuels will be developed, but will play only a minor role in the future mix, in particular for the transportation sector |
| 2.4 | Biofuels from microalgae will be produced commercially, but only in the mid to long term |
| 2.5 | Advances in strain identification and process engineering are key factors in the development of the technology |
| 2.6 | The nature of the cultivation system, closed or open, will depend on the production quantities, type of nutrients required, waste streams available and strains used |

**Table AI.**
Statements of Themes 1, 2 and 3

(*continued*)

| | |
|---|---|
| 2.7 | The microalgae cultivation process will be increasingly used integrated in existing industrial processes, usually not related with energy production and for waste treatment and/or carbon capture purposes |
| 2.8 | Different strains of microalgae will be used depending on the nutrients and/or waste streams available, and particular local climatic and water availability conditions. No single strain will be dominant one |
| 2.9 | Open pond cultivation, or similar, will dominate the future production systems, although for small production involving the processing of waste streams the close cultivation systems will be also used |
| 2.10 | The main aspects that have to be considered in the process development are improving its overall energy efficiency, the ability to produce other high value products, or the possibility to integrate it in other process under the biorefinery concept umbrella |
| 2.11 | The reduction in the dependence in oil imports, and the potential development of local and national economies, is a relevant factor in the development of the area |
| | *Theme 3: sustainability* |
| 3.1 | The environmental sustainability of microalgal derived biofuels is a potential problem |
| 3.2 | The utilization of genetic modified organisms may represent a potential problem in the diffusion of algal biofuels |
| 3.3 | Open pond cultivation is more environmentally friendly than PBRs cultivation |
| 3.4 | Closed PBRs cultivation is more environmentally friendly than open pond cultivation |
| 3.5 | The need to reduce world's $CO_2$ emissions is a key advantage for algae biofuels |
| 3.6 | The production of algae biofuels in large scale could generate potential impacts on local ecosystems from new algal species |
| 3.7 | The production of algae biofuels in large scale could generate potential impacts on water reserves |
| 3.8 | Although microalgae can be used to capture $CO_2$, the actual overall life cycle carbon balance is key aspect to consider |
| 3.9 | The potential of biofuels from microalgae to be carbon neutral is a key factor concerning their sustainability |
| 3.10 | Some potential undesired environmental aspects may arise from microalgae cultivation, as for example, increased emissions of $NO_x$ and/or methane |
| 3.11 | The environmental impacts of energy consumption is the key factor concerning the sustainability of the microalgae cultivation |
| 3.12 | The potential to use waste streams and/or easily available renewable nutrients is a key factor in the overall system sustainability |

**Table AI.**

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