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Food and feed products from micro-algae: Market opportunities and challenges for the EU

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Abstract. Micro-algae are a new and promising source of nutrients. The main products obtainable are dried algae with high nutrients content and high-value compounds such as fatty acids, pigments and anti-oxidants. This paper analyses the market and the economic opportunities of micro-algae-based food and feed sectors in the EU through an integrated methodology composed by literature search, interviews to experts and Delphi survey. Results show that the quantities produced and the market size of nutrients obtained from micro-algae are still significantly smaller in comparison to the ones derived from cereals and other commodity crops, but that the sector has seen an impressive and unique growth. Despite the challenges due to the climatic conditions together with the insufficient domestic demand and the complexity of the EU Novel Food regulation, the survey revealed that the EU can improve its market position in the next decade, thanks to its scientific and technological capacity and its dominant position in the global agri-food markets. New micro-algae-based products can be developed for foreign markets, and the improved global production share of European firms (presently of about 5%) may be the result of strategic acquisitions of foreign companies.

Key words: Micro-algae; nutrients; competitiveness; food markets; expert interview; Delphi survey.

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1. Introduction

In 2012, the European Union (EU) adopted a strategy entitled “Innovating for Sustainable Growth: A Bioeconomy for Europe” (EC, 2012). This strategy proposes a comprehensive approach to increase sustainable productions and limit the negative impacts on the environment. The EU is hence releasing large funding for improving the innovative and sustainable use of renewable resources, while continuing in satisfying the demand for food, energy and industrial products.

Marine resources are raising big expectations in the context of the EU bioeconomy, and micro-algae are particularly attractive as source of a wide variety of high-value molecules for diversified uses. The chemical, pharmaceutical, cosmetic and energy industries are exploring the potential of micro-algae, but it is the nutrition sector that seems to potentially benefit more from micro-algae technologies (Pulz and Gross, 2004).

Algae have been exploited for centuries as food and feed. Already in the 1950s, Burlew (1953) proposed the use of algae as candidates for alternative protein sources to face global food demand, and in the 1960s Japan started the first industrial scale production of the micro-algae species *Chlorella* for human consumption. By the 1980s, large-scale algae production facilities were established in Asia, India, the US, Israel and Australia (Enzing *et al.*, 2014). More recent technical improvements, like new design in production systems and developments in the field of micro-algae biotechnology, led to promising research programs that proved the possibility of obtaining different high-value nutrients from micro-algae, such as carotenoids, phycobilins, fatty acids, sterols, polyhydroxyalkonates and polysaccharides (Borowitzka, 2013).

These recent achievements renewed the interest in micro-algae as a sustainable source of food/feed commodities with enhanced nutritional and functional quality. Micro-algae have been promoted as having the potential of supplying a substantial portion of the EU food and feed

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market with a limited production surface (Draaisma *et al.*, 2013), showing important implications for the reduction of world food insecurity (Ahsan *et al.*, 2008; OECD, 2013).

The potential of micro-algae for the production of new compounds (not only nutrients but also bio-fuels, bio-chemicals and other bio-products) is being widely explored. The R&D scenario is very active in researching the options offered by biotechnology in micro-algae. In particular, genetic engineering can represent a relevant source of innovation in the field of algae and micro-algae, but the technology is still immature and far from commercial applications (Enzing *et al.*, 2014).

Although the research activities on micro-algae-based nutrients are very promising, the products currently on the market are still limited. There are two main categories of food market products obtained from micro-algae (Enzing *et al.*, 2014). The first category is dried algae (in particular the micro-algae species *Chlorella* and *Spirulina*) with high nutrients content, especially of vitamin B12, C and D2. These micro-algal products can be directly sold as dietary supplements and have the potential to be used in bulk commodities as sources of proteins and carbohydrates. The second type are specialty products isolated and extracted from the micro-algae that can be added to food and feed to improve their nutritional value. These high-value compounds are pigments (e.g. astaxanthin), anti-oxidants (e.g. beta-carotene), proteins (e.g. phycocyanin) and fatty acids (e.g. omega-3, docosahexaenoic acid - DHA and eicosapentaenoic acid - EPA).

A number of conditions are still to be met to exploit the production and commercial potential of micro-algae products in the EU. From a regulatory point of view, the European regulations on novel food and novel food ingredients, on food safety, and on nutrition and food health claims affect the marketing of micro-algae products. The safety of the products must be assessed before their launching on the markets, but restrictive regulatory requirements can delay the pace of commercialization. In particular, the EU food safety regulation requires the

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assessment of toxins, allergens or other harmful compounds potentially produced by the algae.

Hence, the correct and undoubtful identification of the algae strain is a fundamental step to ensure the safety of large-scale industrial productions of algae (Enzing *et al.*, 2014).

The possibilities of increasing the production and commercialization of micro-algae high-value nutrients depend also on a series of market and economic factors, but the lack of public economic and market data make it difficult to evaluate their effective industrial potential for the support of funding and policy decisions. Data are mainly hold by private companies and are accessible at very high costs, usually not affordable by researchers.

The literature about the economic viability of these products and their markets is scarce. Some publications mainly review the high-value molecules of interest for food and feed that can be extracted from micro-algae (Dufossé *et al.*, 2005; Chacón-Lee and González-Mariño, 2010; Draaisma *et al.*, 2013), but without analyzing the market opportunities of these products. Other authors provide estimates of global production of specific molecules, such as carotenoids (Milledge, 2012; Borowitzka, 2013) and fatty acids (Ismail, 2010). The most relevant studies providing figures for a comprehensive range of micro-algae-based food products are Pulz and Gross (2004) and Spolaore *et al.* (2006). All these authors provide global pictures of the micro-algae-based food applications, but none provides evidences on the development of this sector at EU level.

This paper discusses the main results of the European Commission (EC) project "Microalgae-based products for the food and feed sector: an outlook for Europe" (Enzing *et al.*, 2014)¹, contributing to the existing literature in several ways. First of all, to overcome the problem of

¹ The paper is not limited to presenting the results of Enzing *et al.* (2014), but includes additional details and research outcomes. In particular, section 2 of the paper provides a full explanation of the Delphi methodology, presenting its pro and contra and motivating its application for the micro-algae sector; section 3 contains the results of additional data search and discusses the constraints of the publicly available trade data; figure 1 has been originally elaborated for this article; in section 4.2 we present in details the revision of the Novel Food regulation, discussing its implication for micro-algae products.

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the scarcity of economic and market data, we designed a methodology that integrates literature review with primary information based on interviews and electronic (Delphi) survey to selected experts. Secondly, we examined all food and feed products derived from micro-algae (including nutrients) that are available on the market, considering both the global situation and the EU sectors, and taking into account the safety and regulatory issues. Thirdly, we analyzed the technical and non-technical factors affecting current and future production costs and determining the competitiveness of the EU sectors. Finally, the study aims to shed light on the industrial and market potential of micro-algae as a source of food/feed products and nutrients, going beyond the laboratory opportunities and discoveries, but exploring the development of the industrial sector.

Results from our research show that, although the market for micro-algae-based food and feed products has a great potential for future growth worldwide, the actual contribution of micro-algae-based products to human and animal nutrition is quite limited. This is due to the small scale of production and to the high production costs, especially in comparison with traditional commodities. The EU has a leading position in innovative research on micro-algae and its high-quality traditional agri-food sector can pull micro-algae-based products. These advantages can be exploited in particular for those compounds whose traditional sources are becoming more and more costly, such as omega-3 from fish oils. However, the unfavorable climatic growth conditions, the insufficient domestic demand and the complexity of the Novel Food Regulation (EC, 1997) for the commercial authorization of new products are the major factors limiting the development of the European micro-algae sector.

The remainder of the paper is structured as follows: section 2 presents the methodology applied. Section 3 shows the results of the data and literature search integrated with information from the experts' interviews. Section 4 presents the results of the survey to experts and, finally, section 5 concludes and provides future perspectives.

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2. Methodology

The main problem in analyzing the European sector of micro-algae-based food/feed products and nutrients is the lack of public historical data. Our methodology is designed to overcome this problem and to retrieve original information on the current European sector and on its future development and trends. It consists in an integrated three-step methodology, with a progressively increasing level of details, not available before.

The first step is a data and literature search to obtain the current state of knowledge on food and feed products derived from micro-algae as a starting point. In the second step, we identified and interviewed selected experts in specific fields on the base of the knowledge gaps revealed by the literature and data search. In the third step, we collected primary information surveying experts on the EU sector for micro-algae-based food and feed products. In what follows, we describe the details of each step.

2.1 Data and literature search

The literature search was performed mainly in the database Scopus, through the access of Wageningen University. Additionally, other publicly available databases have been employed to complement the search. The topics of the literature search were the following: production systems of micro-algae; R&D and economics of micro-algae-based agri-food products and production; micro-algae safety and regulation in the EU. For each topic, a set of keywords were selected for the search, together with a specific time range (see Enzing *et al.*, 2014, for details on keywords and time range).

To complement the search for economic and market data, also the following databases on production and trade have been consulted: Eurostat, FAOSTAT and the Commodity Trade Statistics Database (Comtrade) of the United Nations.

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2.2 Interviews with experts

The literature search revealed a number of information gaps on market data, production systems and costs of algae-based food/feed products and nutrients in the EU. These gaps are filled through interviews with selected experts, who were asked to validate the figures collected through the literature search and to answer questions on the following topics: micro-algae production systems; global distribution of micro-algae production; micro-algae production costs and molecules extraction costs; European market figures for traditional and micro-algae-based products; EU regulation for authorization of micro-algae products.

Experts' selection was performed according to different criteria. First of all, their expertise in fields related to the scope of our study, like economics, production systems, agri-food products, R&D activities and legislations of micro-algae. Secondly, their affiliation had to refer to academies, industries or regulatory agencies dealing with the micro-algae sector. Finally, experts were favored when possessing scientific publications and participation in international conferences in the field of food/feed products derived from micro-algae.

Through this thorough selection, a list of 219 experts from all over the world was built, the majority of them coming from the private sector (135) and the rest from academia and public sector (68).

The long-list of experts has been used for both the interviews and the survey (see next section). For the interviews, experts with the highest number of scientific publications and the highest degree in the working position were selected and invited by e-mail to participate in the interview. Of the 18 experts contacted, 10 accepted to be interviewed. The majority of the experts interviewed are employed in the private sector and in the academia, while one expert works for a public regulatory agency.

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2.3 Survey strategy

The survey was conducted on all the 219 experts identified in the long list (see previous section for experts' selection criteria) using a questionnaire divided in two sections².

The first section consists in a standard electronic survey with the objective of collecting information on the current factors affecting the competitiveness of the EU for micro-algae-based food and feed products. The standard-survey part of the questionnaire explores the following topics: production costs, EU competitiveness and EU drivers and constraints in the sector of micro-algae-based food and feed products.

The second section is designed to collect experts' opinions on the future trends and perspectives for the EU through a Delphi survey method. The Delphi part of the questionnaire includes questions to assess the market position of the EU in the micro-algae field and questions on the potential of food/feed products derived from micro-algae to substitute traditional (crops) products.

The Delphi survey is a well-known, recognized method for gathering information in absence of historical statistical data. It was originally developed in the fifties in the US for uses in policy making, to establish consensus among experts regarding different policy issues and it is particularly suited to obtain forecasts on future sectorial developments (Linstone and Turoff, 1975). The Delphi method consists in data collection based on reiterated exchange of opinions between experts, with the help of a written questionnaire containing open and/or closed questions. The questions of the Delphi method are directed again to the experts in successive rounds. The number of rounds can vary, but rarely exceeds three rounds (Wentholt *et al.*, 2009). In the second round, experts receive the (aggregated and anonymous) results of the first round

² The questions of the interviews and the full questionnaire of the survey are available in the Annex B of the EC report on micro-algae-based products (Enzing *et al.*, 2014).

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and are requested to revise their previous answers if necessary. This process has several advantages. First, the aggregated response is less likely to contain mistakes thanks to the reiterated revision process of the answers (Rowe and Wright, 1999). Second, the anonymity guaranteed by the questionnaire allows the free expression of views and the exchange of opinions of respondents, avoiding social or political pressures that often emerge in groups' experiments and that can lead to phenomena such as "group-thinking" (Wentholt *et al.*, 2009). Finally, it permits to collect information in situation of lack of historical/economic/technical data (Rowe and Wright, 1999). This last advantage is fundamental for our analysis, since no public data or databases on micro-algae-based food/feed products and nutrients are available. With this strategy we obtained a probable route of future developments on micro-algae products, while having always in mind that the information is based on opinions.

On March 26th 2013 the questionnaire was sent to the list of 219 experts through on-line survey software. The questionnaire contained both questions of the standard survey and of the Delphi first round. For each question, participants were provided with an introduction, a statement and a certain number of closed answers related to the statement. The number of experts who accepted to participate in the survey was 88. On April 22nd, they received the second round of the Delphi part of the questionnaire, and 28 experts accepted to participate also to the second round. This number is in line with the suggested sample size for second round Delphi surveys, which ranges between 10 and 30 experts (Aschemann-Witzel *et al.*, 2012).

3 Current markets and production aspects of micro-algae-based nutrients

This section presents the results of the data and literature search combined with the information collected from the experts' interviews. One of the most relevant sources of data on algae is the

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trade statistics provided by UN Comtrade. According to Comtrade data³, in the period 2010-2012 the top three world exporting countries of algae were China, Indonesia and South Korea, with more than 125 million dollars/year of algae-based products each. All these countries have a long tradition in the production and consumption of micro-algae in food and feed. In the same period, the main exporter to the EU was Chile, with an annual average of 13 million dollars/year of algal products, followed by Indonesia and the US. The most important EU exporters in 2010-2012 were Ireland, France and the Netherlands, but with values of one order of magnitude lower with respect to China. The most important countries importing algal products from the EU were the US, Australia and South Africa.

Although Comtrade provides relevant time series of imports and exports bilateral trade flows, these data reveal important limitations in the analysis of algae-based food/feed products and nutrients. First of all, it is not known in detail which products are contained in the code "292.97 Seaweeds and other algae". It is possible that the values are generally referred to the algal biomass (dried or not) but it is not clear if they include also micro-algae and the high-value products extracted from them, nor it is clear if the data concern food/feed use or other industrial uses. A focus on the industrial use could explain the relevant position of Ireland, which produces seaweeds in the North Sea for the extraction of alginic acid to be used in the paper and textiles sectors. Moreover, these data also include re-exports and re-imports, hence it is not possible to understand the comparative advantage of countries in producing micro-algal biomass. Finally, Comtrade does not provide data on production and consumption, hence these are still unknown.

³ In order to obtain the most recent data we used the Standard International Trade Classification (Revision 4). The code used is "292.97 Seaweeds and other algae" included in "Section 2 – Crude materials, inedible, except fuels" mostly containing agricultural raw materials.

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Other existing data on algae-based food/feed products and nutrients are mostly owned by private companies and are mainly world estimates, with little details on market information at product level. Figure 1 shows the geographical distribution of major companies operating in this sector, and table 1 provides a review of market data about the micro-algae-based food/feed products and nutrients.

Data in table 1 refer to global productions, but the current contribution of the EU is quite limited. Interviewed experts estimated the EU production share at around 5% of the global figures in table 1. Moreover, one of the expert underlined that *[the EU has a strong food & feed processing sector and may take advantage of it for the downstream processing or for R&D and technology exports related to micro-algae-based products. But the high-volume production is likely not to be competitive in the EU due to climatic constraints (mainly the relative low temperature)]*.

Looking at the volumes of the single products, the production of dried whole algae *Spirulina* and *Chlorella* is the largest, although it is concentrated in few companies based mainly in Asia and the US. The estimated global production volumes of *Spirulina* and *Chlorella* is 5,000 and 2,000 tons of dry matter/year respectively and the production values about 40 million dollars/year each (Milledge, 2012; Spolaore *et al.*, 2006).

During the interview, one expert explained that the geographical distribution of the production of whole dried algae is *[mainly in favor of US (South-West), Asia and Australia. Production in Northern/Central/Western EU is not very competitive, since yields are on average 50% of the other locations, due to lower solar input. High-volume production of relatively low-value micro-algae products will therefore not be a competitive industry for the EU]*. This is also confirmed by the fact that only three out of ten European companies in the micro-algae sector produce dried algae (Figure 1).

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The production of high-value molecules from micro-algae is geographically more dispersed than dried algae (Figure 1). The total market size and production volumes of micro-algae-based food and feed products are still smaller in comparison to the ones derived from other sources, traditionally cereals or other commodity crops. However, it is worth noting that, since the beginning of 2000, micro-algae production for food and feed showed a 5-fold increase (Ismail, 2010).

Micro-algae-based high-value molecules have smaller production volumes but larger market value than dried algae. Carotenoids are the most important molecules extracted from micro-algae in terms of volumes. The pigment astaxanthin is extracted from the micro-alga *Haematococcus Pluvialis* and is currently the most produced carotenoid (Borowitzka, 2013). On the other side, omega-3 fatty acids are the products obtainable from micro-algae with the highest commercial value.

The differences in the geographical distribution of the food and feed products obtained from micro-algae are linked to the different climate conditions and, consequently, to different production systems. There are two main production systems for micro-algae, namely open and closed systems (Enzing *et al.*, 2014). The most common open systems are outdoor ponds, which are highly dependent on the climatic and environmental conditions. Outdoor ponds are mainly intended for the production of dried micro-algae due to the lower operational costs, which make the large production of dry micro-algae biomass more profitable (source: experts interviews). However, according to experts, today it is not possible to avoid contamination and for this reason many cultures crash in open systems. Thus, it is more feasible to grow algae in semi-closed systems, which seem to be the cheapest system for the production of food and feed biomass. For open or semi-closed systems, the major problem is to find locations with adequate climatic and environmental conditions. Because of the needs of higher temperatures and sun-

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light intensities, open systems are more common in southern locations (Terry and Raymond, 1985).

Closed systems are typically called photobioreactors (PBRs). There is a large variety of them and they can be placed either out- or indoor. Given that PBRs are less dependent on the climatic and environmental conditions, they can be used also in northern locations. Because their installation and use is very expensive, they are mainly suited for the production of micro-algae containing high-value molecules to be extracted (Zijffers *et al.*, 2010), and this was also confirmed by one of the experts interviewed.

Recent estimates by Norsker *et al.* (2011) show that the production cost of 1kg of micro-algal biomass strongly depends on the production system and its scale. In plants of 1 hectare of surface, 1kg of micro-algal biomass is 41-44% more expensive in ponds than in PBRs. These higher costs are mainly due to the higher labor intensity of open systems. On the contrary, in plants of 100 hectares of surface, PBRs result 27-30% more expensive than ponds, mainly due to higher energy consumption. However, the estimates for production costs of algal biomass can widely vary depending on different assumptions (see Christiansen *et al.*, 2012).

Currently, the low volumes and high production costs of micro-algae, especially in comparison with traditional food commodities (for instance, annual global wheat production is about 100,000 times bigger than micro-algae biomass production), encourage the utilization of high-value molecules for human rather than for animal consumption. To increase the economic efficiency of the production of micro-algae-based high-value compounds, and eventually to extend their use to animal feed production, it is of utmost importance that a parallel market is developed for the left-over biomass remaining after the extraction of high-value components, for example for the production of biofuels. However, according to one expert, *[today there is no such a market because of the low volumes of algal biomass produced and the relatively*

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higher price with respect to alternative biomass sources, like in particular the residuals from the agricultural activity].

The large-scale industrial production of proteins and carbohydrates from micro-algae for the agri-food sector would require higher production volumes and a dramatic reduction of production costs to be competitive with agricultural commodities. What emerged from the interviews is that *[food from micro-algae cannot yet replace other standard food sources as vegetables, thus micro-algae can be used as source of ingredients in added-value/high-nutritional foods. This is even more relevant for the feed market where micro-algae biomass cannot replace vegetables or cereals as protein source. Micro-algae can only be incorporated as enriching factor in early stages of animals' development to improve the health and growth of individuals]*. Therefore, according to the results illustrated so far, the actual contribution of food and feed products derived from micro-algae to food security seems to be still rather limited.

4 Results of the survey

We first present the results of the standard electronic survey (first section of the questionnaire) on the factors influencing costs and competitiveness of the EU sector of micro-algae-based food/feed products and nutrients. Secondly, we report the results from the Delphi survey, forecasting the future developments of the EU sector. It is important to note that there were not significant differences in the surveys' answers between experts of different affiliations (academy, private sector or others), neither between experts from different countries. For this reason, we treated the sample as an aggregate, without distinguishing among different affiliations or countries. The complete text of the statements is available in Enzing *et al* (2014).

4.1 Current competitiveness of the EU

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In order to assess the level of the EU competitiveness in micro-algae-based food and feed products, participants were asked to assess two different statements and to answer to one direct question, through a standard electronic survey.

The first statement concerns the production costs. Respondents were asked to choose among technical and non-technical factors that would contribute to achieve a decrease of production costs, so that in 2020 most of the products described in the previous sections would be micro-algae-based. Moreover, experts were asked to comment on their choice.

Among the technical factors, more than 60% of experts indicated that increasing the production scale is the most important factor in order to reduce production costs (Figure 2). According to experts, volume constraints of the market and related higher prices can be improved by enhancing cooperation and exchange of information between producers and customers. Experts also believe that several strategies to enhance biomass productivity must be put in place, such as PBRs design, identification of new nutrient sources and genetic modification of the algal strains.

Among non-technical factors, experts mentioned companies' investments, legislation and access to credit as the main bottlenecks to reduce production costs. One participant also highlighted the importance of distinguishing between food and feed markets. According to him, companies focus more on food products because the high production costs and the low production volumes make the feed sector less attractive. In order to use algae as bulk feed ingredients it is needed a cost effective up-scaling of the production.

The second statement to be assessed by experts concerns the factors affecting the EU competitiveness in R&D for the micro-algae-based food and feed sector. Experts were asked to determine which factors would enable the EU R&D up to a level that, by 2020, the new micro-algae-based products entering the market would require lower production costs and therefore improve the competitiveness of the EU industry in this sector.

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Experts state that different factors are affecting the performance of the EU in the micro-algae sector (Figure 3). The most relevant challenges to improve the European competitiveness in micro-algae R&D are the reduction of production costs and technical innovation. Half of surveyed experts also highlighted the need of a better inter-institutional cooperation, in particular between universities and companies. Additionally, experts deemed necessary that public institutions dedicate less investments in micro-algae R&D and put more efforts into improving the products' approval process.

In the electronic survey, experts were also asked to indicate what, in their opinions, are the drivers and constraints of the micro-algae-based food and feed sector in the EU.

Experts highlighted three strengths of the EU: its scientific and technological capacity in the micro-algae sector; its active R&D funding policies; and its competitiveness on the global agri-food markets and related infrastructures.

Participants underlined that the EU can rely on human capital with high-level engineering and technical skills, especially in the micro-algae biofuel sector, which may boost also the food sector thanks to the transfer of technology spill-overs. In addition, in the EU there are many small enterprises dealing with micro-algae products that show a very intense R&D activity and produce significant technological innovation in the sector. These advances are enhanced by the priority of the EU towards the bioeconomy sector and the amount of funds available for R&D.

Moreover, the EU can achieve a solid position in the micro-algae-based food and feed sector thanks to its high quality and solid tradition in the agri-food sector. The European endowment of infrastructures for commodities transports and commercialization, as well as the structure of the food and feed industry composed by multinational companies represent strategic advantages for the development of commercial micro-algae food and feed products. Furthermore, consumers' preferences in the EU are largely in favour of natural and healthy products, whose

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demand is constantly increasing. Micro-algae-based food products, thanks to their nutritious content and their natural origin, seem to perfectly reflect this trend.

In opposition to these strengths, experts indicated some important weaknesses of the EU, namely the geographical position, financial and economic aspects, and the strict regulation.

The EU is characterized by a suboptimal climate for the production of micro-algae in the majority of the Member States. Only southern countries such as Croatia, Greece, Italy, Portugal and Spain possess the optimal sun hours and intensity, which in the northern countries are insufficient, especially during winter. Also the levels of rainfalls and the temperatures are inadequate for algae growing in northern EU countries. As a consequence, the EU lacks sufficient surface area for extensive outdoor production of micro-algae while at the same time has relatively high land and labour costs.

Moreover, the EU lacks of a historical tradition in consuming algae, in contrast with South-East Asia, thus the European demand of these products is lower. Finally, further technological developments are hampered by relatively restrictive regulations on genetically modified organisms (GMOs), and a negative attitude of the public opinion towards this technology.

4.2 Future perspectives for the EU

The Delphi survey was carried out to forecast future developments and competitiveness of the European micro-algae-based food and feed sectors. Experts were asked to assess and reach consensus on two separate statements, through a two-round process of answers' revision. For each statement, experts were asked to select the most likely time period in which the statement would be achieved and the factors affecting the achievement of the statement, and to comment on their choices.

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The first statement of the Delphi survey declares that the EU will become market leader in micro-algae-based products for the food and feed markets, although its market position at the moment is rather limited.

Figure 4 shows the results for this statement. In the first round, a large proportion of experts expect the EU to become market leader of micro-algae-based food and feed products later than 2020 (38%). Only the 8% indicated that the EU will be market leader before 2016, and a total of 18% does not believe that this would happen at all. According to the distribution of respondents, there is no significant discrepancy in terms of levels of competence. There only seems to be a tendency among experts with higher level of competence to answer ‘Never’, and among mid-level competence to answer ‘After 2020’.

According to respondents, scientific and technological factors as well as the global development of the food and feed markets (including the competition of micro-algae-based products with those from other sources) are clearly the most important factors driving the future development of the European market position.

About the scientific and technological factors, many respondents stressed that the EU can be market leader exclusively in the sector of high-value molecules by PBRs, whose production is less dependent on the (unfavourable) European climatic conditions. In alternative, the leadership can be achieved through large multinationals with foreign direct investments in the southern hemisphere, but not through outdoor production in the EU.

Moreover, some respondents emphasized the role of policies and regulation in shaping the future markets of micro-algae. There are two EU regulations that most closely affect production and commercialization of food/feed products derived from micro-algae: Regulation (EC) No 178/2002 on Food Safety (EC, 2002) and Regulation (EC) No. 258/97 on Novel Food (EC, 1997). The Novel Food Regulation (currently being revised by the EC) illustrates the requirements for the authorization procedure of new food and feed products in the EU,

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including the ones from micro-algae, which represents the first fundamental step for their commercialization. Applicants for the authorization have to prove that new products are as safe to animal and human health as the traditional ones (substantially equivalent) and provide scientific evidence. One expert commented that the EU has a competitive disadvantage in the field of food/feed products derived from micro-algae due to restrictive requirements of the regulation, and therefore has limited chances to become market leader because of the regulatory environment. According to this expert, the Novel Food Regulation in particular is seriously hampering the market access of many products, because of long and costly requirements.

In this regard, the ongoing revision of the existing Novel Food Regulation by the European Commission⁴ has the scope of centralising the food risk assessment and risk management processes from Member States to EU level and to simplify the authorisation procedure, in particular for traditional foods from third countries. This revision is aimed to guarantee shorter and less expensive authorisation processes for the access of new and innovative food on the EU market, while still maintaining a high level of consumer protection.

Despite the disadvantage identified due to the strict regulatory requirements, according to one participant to the survey, the EU has the potential advantage to be the first-mover given its breakthroughs in the algae' technology. This can be further exploited, but only by shifting the funding support from the R&D phase to the commercialisation of products.

In the second round of the Delphi survey (Figure 4), the respondents were asked to go into further details with respect to the expected achievement date of the same statement described above. The majority of the experts (30%) selected the period 2020-2022, thereby confirming the previous round. Respondents also reached clear consensus towards the scientific and technological factors as main drivers of the future European market position.

⁴ At the following web address is available a detailed description of the proposal for revision of the Novel Food regulation: http://ec.europa.eu/food/food/biotechnology/novelfood/initiatives_en.htm

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The second statement of the Delphi survey regards the potential use of micro-algae-based food/feed compounds in substitution of synthetic or other natural sources. Experts were asked to give their opinion about the time in which they think that astaxanthin, beta-carotene, phycocyanin, EPA and DHA in the food and feed market would primarily derive from micro-algae, instead of other sources like chemical synthesis, carrots, blue-algae (cyanobacteria), fish fat and walnuts respectively.

Figure 5 shows the results of this assessment. In the first round, the majority of the respondents are divided in two: the ones expecting that high-value molecules for food and feed will primarily derive from micro-algae in 2016-2020 (69%) and the ones expecting this achievement later than 2020 (67%). Solely 11% of experts answered that it will never occur, and even less answered that it will occur earlier than 2016. Overall, the most sceptical experts seem to be the ones that are very familiar with the subject, compared to the ones rather familiar. The discrepancy is however insignificant: 18% of the very familiar against 7% of the non-familiar experts.

Also for this statement, the most important drivers are the scientific and technological factors and the development of the global food and feed markets, chosen by 69% and 56% of respondents respectively. One respondent commented that [*the extraction of fatty acids from fish is increasingly expensive, and this will favour fatty acids production from micro-algae*]. The higher costs for fish fatty acids may be due to [*the overfishing of salmons, which is leading to higher prices of fish oil*].

One expert highlighted that future production sources of astaxanthin and phycocyanin will not coincide with the ones of EPA and DHA. According to him, in the future algae will be the main source of astaxanthin and phycocyanin but not of EPA and DHA, whose production from fish oil is already well established. More sceptical experts answered that further microbiological sources such as yeast, fungi and bacteria could potentially be more productive than micro-algae.

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The second Delphi-round for the assessment of the statement (Figure 5) clearly converges (with 34% of respondents) to the 2020-2022 period. Moreover, respondents reached consensus on the scientific and technological aspects as the most important factors affecting the substitution from traditional to micro-algae-based sources of high-value molecules for food and feed.

5. Conclusions

This paper analyses the market and the economic characteristics of the micro-algae-based food and feed sector in the EU. We used an integrated methodology composed by literature search, interviews to selected experts and an electronic (Delphi) survey to analyze the current and future competitiveness and opportunities for the EU in the micro-algae sector.

Currently, the food and feed products obtained from micro-algae available on the market are dried whole algae and a number of high-value molecules and colorants. Many promising research programs aimed at developing new micro-algae-based food and feed products with a great potential of reaching the market are in progress, but the commercial production of micro-algae as an alternative source of proteins, fatty acids and carbohydrates is still an infant industry, not yet able to significantly contribute to the reduction of the food-feed insecurity world-wide. Currently, most producers of micro-algae-based commercial products are located in Asia or Australia and are showing an impressive growth, despite the actual production volumes are still not competitive with traditional agricultural commodities.

Estimation of the production share of food/feed micro-algae products owned by European companies is about 5% of the global market. The majority of the surveyed experts consider that the EU can significantly improve its market share thanks to the scientific and technological developments in the field of micro-algae R&D and its current leading position in the global agri-food market. In fact, many experts are of the opinion that the EU can be market leader

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already in the next decade. The increased production share by European companies can also be driven by recent strategic acquisitions of foreign companies, especially in Australia and in the US. Moreover, other additional factors can contribute to the development of the EU market of micro-algae products, in particular of fatty acids: the increasing costs of high-value molecules (like nutraceuticals) from traditional sources and the better quality of the micro-algae final products, due to its molecular characteristics.

However, three major factors can limit the European potential: i) the unfavorable climatic conditions of large part of the Northern Europe for low-cost extensive production of micro-algae; ii) the low demand in European countries for micro-algae products, which could be improved by targeted food and nutrition education programs and iii) the complexity of the EU regulation on novel foods, which hampers the authorization of micro-algae-based products for the internal market, although this last aspect is currently being addressed by the EC in its revision of the Novel Food Regulation. These limitations suggest that, most likely, new products developed in the EU will be mainly directed to external markets.

From a research perspective, biotechnology will play a major role in the near future, especially in production systems, as it can contribute to increasing the productivity and reducing the production costs of micro-algae products. Governments and private companies are currently dedicating large investments to stimulate the biotechnological approach on micro-algae. Nevertheless, additional efforts, especially in terms of R&D, are necessary to achieve commercial food and feed products from GM algae, especially in the EU, where the complex GM regulation and the low consumers' acceptance may slow-down the development of this technology.

Further research is needed also to obtain more detailed economic and market data on production volumes, turn-overs, costs and input uses, both at companies level and by country. This would permit to obtain more detailed information on the micro-algae-based food sector in

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the EU and to clarify the actual contribution that micro-algae-based products can provide to the development of the bioeconomy in the EU.

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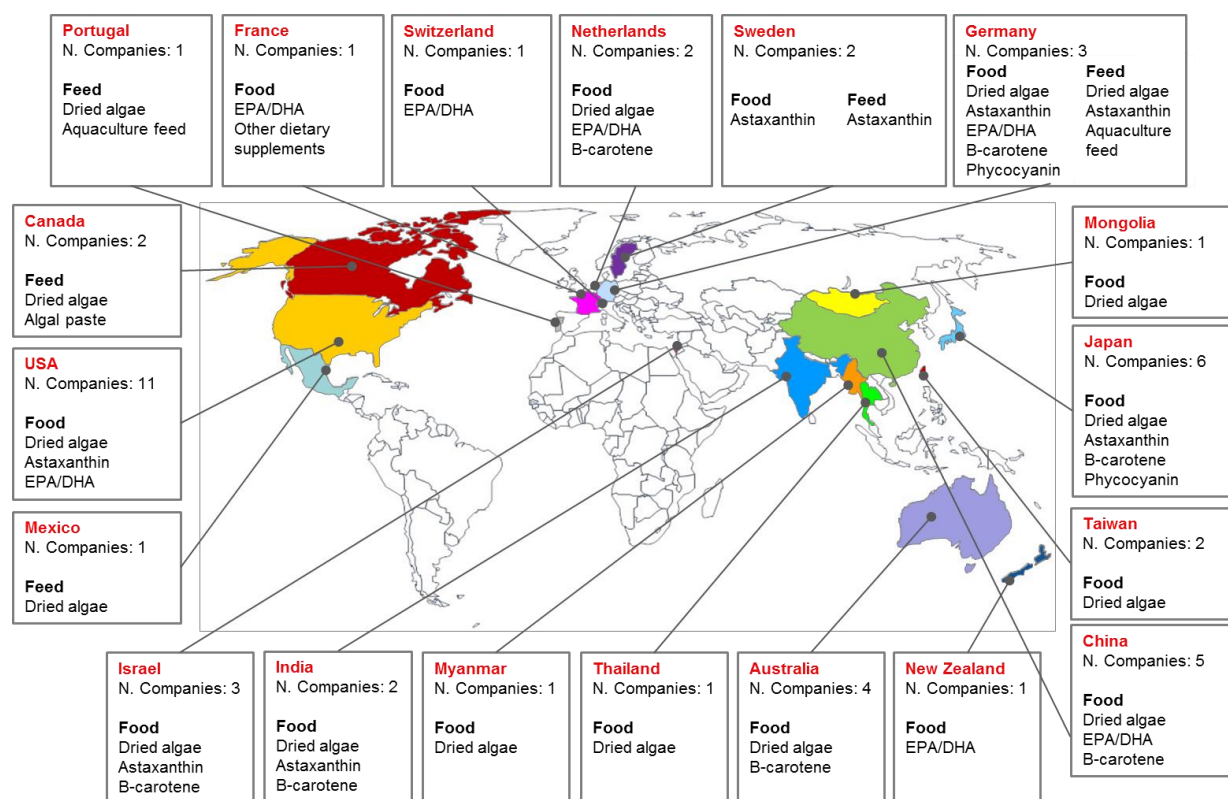
References

- Ahsan, M., Habib, B., Parvin, M., Huntington, T.C., & Hasan, M.R., (2008). A review on culture, production and use of *Spirulina* as food for humans and feeds for domestic animals and fish. *FAO Fisheries and Aquaculture Circular* No. 1034.
- Aschemann-Witzel, J., Perez-Cueto, F.J.A., Niedzwiedzka, B., Verbeke, W., & Bech-Larsen, T., (2012). Transferability of private food marketing success factors to public food and health policy: An expert Delphi survey. *Food Policy*, 37, 650–660.
- Borowitzka, M.A. (2013) High-value products from microalgae—their development and commercialization. *Journal of Applied Phycology*, 25, 743–756
- Burlew, J.S., (1953). *Algal culture from laboratory to pilot plant*. Carnegie Institute of Washington, Washington, D.C., Publication 600.
- Chacón-Lee, T.L., & González-Mariño, G.E., (2010). Microalgae for Healthy Foods: Possibilities and Challenges. *Comprehensive Reviews in Food Science and Food Safety*, 9, 655–675.
- Christiansen, K.L., Raman, D.R., & Anex, R.P., (2012). Predicting cost growth and performance of first-generation algal production systems. *Energy Policy*, 51, 382–391.
- Draaisma, R.B., Wijffels, R.H., P.M. (E. llen), Slegers, P.M., Brentner, L.B., Roy, A. and & Barbosa, M.J. (2013). Food commodities from microalgae. *Current Opinion in Biotechnology*, 24, 169–177
- Dufossé, L., Galaupa, P., Yaronb, A., Malis-Arad, S., Blancc, P., Chidambara-Murthyd, K.N. and & Ravishankar, G.A. (2005). Microorganisms and microalgae as sources of pigments for food use: a scientific oddity or an industrial reality? *Trends in Food Science & Technology*, 16, 389–406.
- EC (1997). Regulation (EC) No. 258/97 of the European Parliament and of the Council concerning novel foods and novel food ingredients. *CELEX-EUR Official Journal*, 43, 1-7.
- EC (2002). Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety. *Official Journal of the European Communities*, L 31, 1-24.
- EC, 2012. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Innovating for Sustainable Growth: A Bioeconomy for Europe. http://ec.europa.eu/research/bioeconomy/pdf/official-strategy_en.pdf.
- Enzing, C., Ploeg, M., Barbosa, M. and & Sijsma, L. (2014). Microalgae-based products for the food and feed sector: an outlook for Europe. In Vigani, M., Parisi, C. and Rodríguez Cerezo, E. (Eds.). JRC Scientific and Policy Reports. https://ec.europa.eu/jrc/sites/default/files/final_version_online_ipts_jrc_85709.pdf
- Ismail, A., (2010). Marine lipids overview: markets, regulation, and the value chain. *Oilseeds and fats Crops and Lipids*, 17(4), 205–208.
- Linstone, H.A., & Turoff, M., (1975). *The Delphi Method: Techniques and Applications*. Addison-Wesley, London.

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- Milledge, J.J., 2012. Microalgae: commercial potential for fuel, food and feed. *Food Science and technology*, 26(1), 28-31.
- Norsker, N.H., Barbosa, M.J., Vermuë, M.H., & Wijffels, R.H., (2011). Microalgal production - A close look at the economics. *Biotechnology Advances*, 29, 24–27.
- OECD (2013). Marine Biotechnology: Enabling Solutions for Ocean Productivity and Sustainability, OECD Publishing.
- Pulz, O., & Gross, W. (2004). Valuable products from biotechnology of microalgae. *Applied Microbiology and Biotechnology*, 65, 635–648.
- Rowe, G., & Wright, G. (1999). The Delphi technique as a forecasting tool: issues and analysis. *International Journal of Forecasting*, 15, 353–375.
- Spolaore, P., Joannis-Cassan, C., Duran, E., & Isambert, A. (2006). Commercial Applications of Microalgae. *Journal of Bioscience and Bioengineering*, 101(2), 87-96.
- Terry, K.L. & Raymond, L.P. (1985). System design for the autotrophic production of microalgae. *Enzyme and Microbial Technology*, 7, 474-487.
- Wentholt, M.T.A., Rowe, G., König, A., Marvin, H.J.P., & Frewer, L.J. (2009). The views of key stakeholders on an evolving food risk governance framework: Results from a Delphi study. *Food Policy*. 34, 539–548.
- Zijffers, J.W.F, Schippers, K.J., Zheng, K., Janssen, M., Tramper, J. & Wijffels, R.H. (2010). Maximum Photosynthetic Yield of Green Microalgae in Photobioreactors. *Marine Biotechnology*, 12(6), 708-718.

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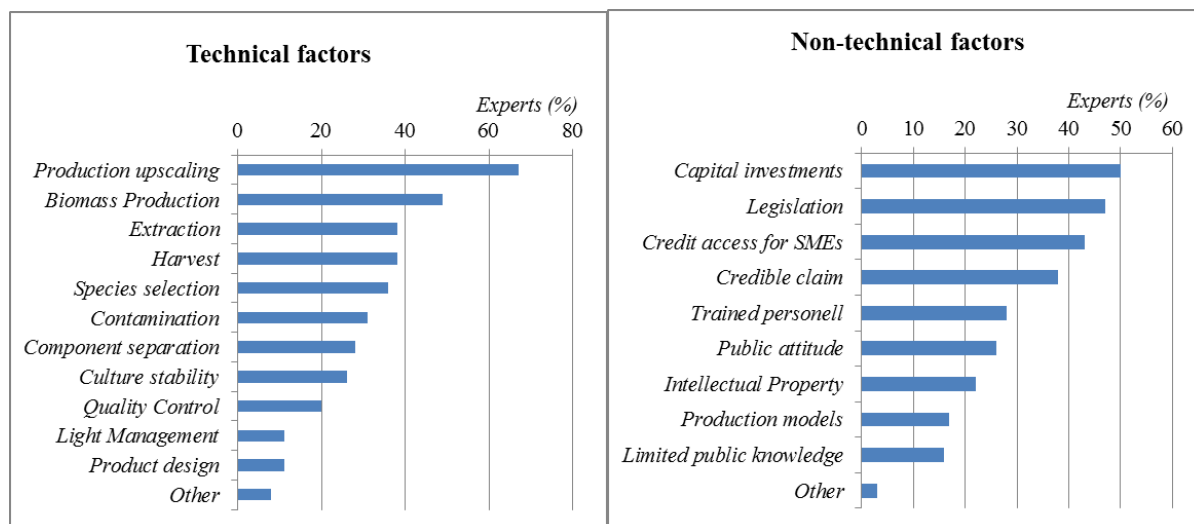
Figure 1 – Global distribution of private companies producing commercial food and feed products derived from micro-algae



Note: data come from experts' interviews and literature review. The map refers to companies headquarters. Number and locations of production plants are not available.

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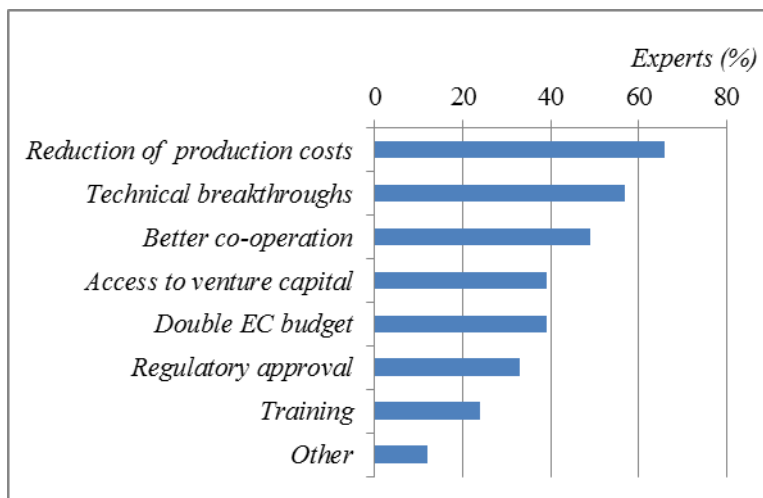
Figure 2 – Technical and non-technical factors influencing production costs of micro-algae-based food and feed products



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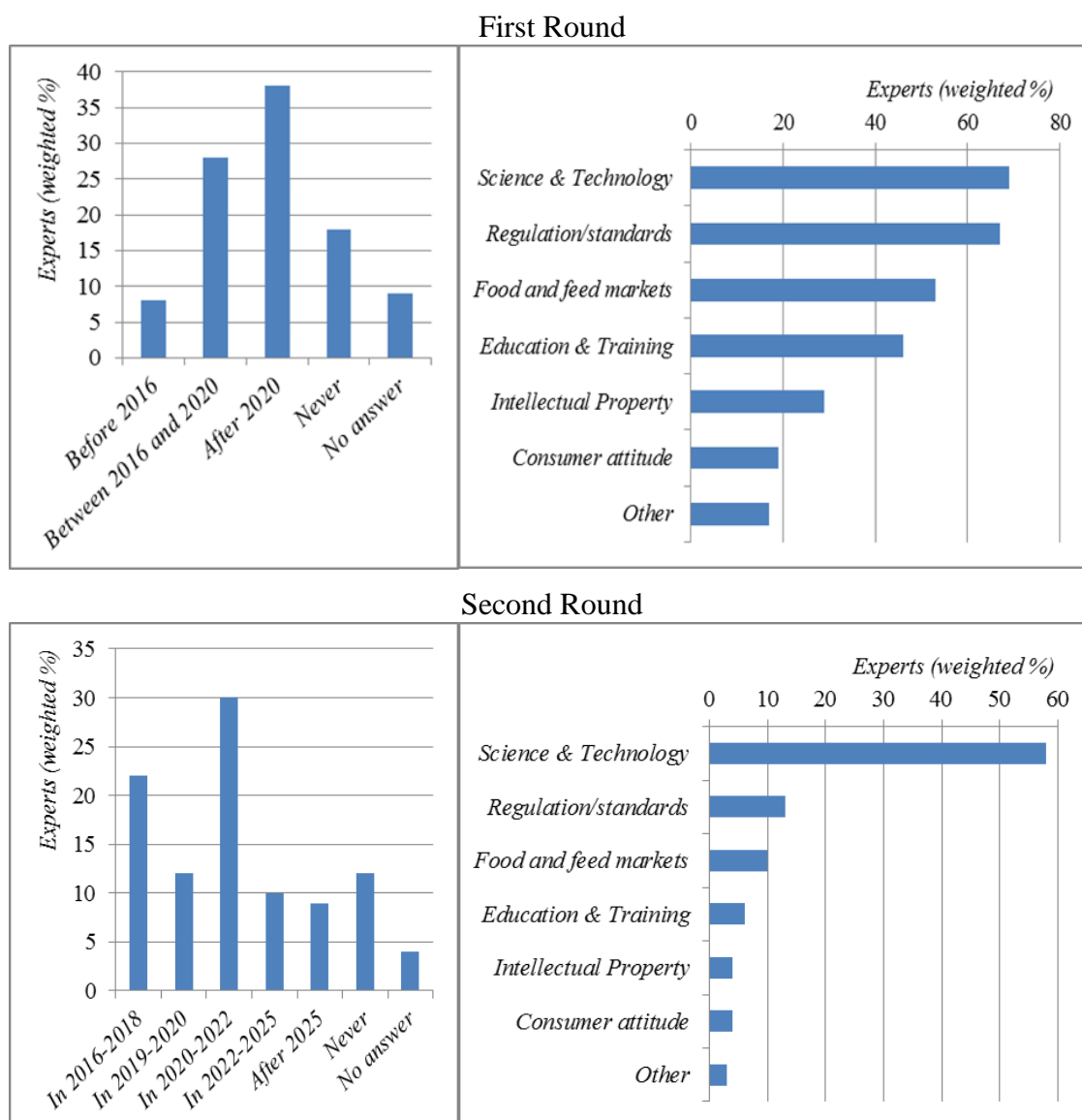
Figure 3 – Factors affecting R&D and competitiveness in the EU



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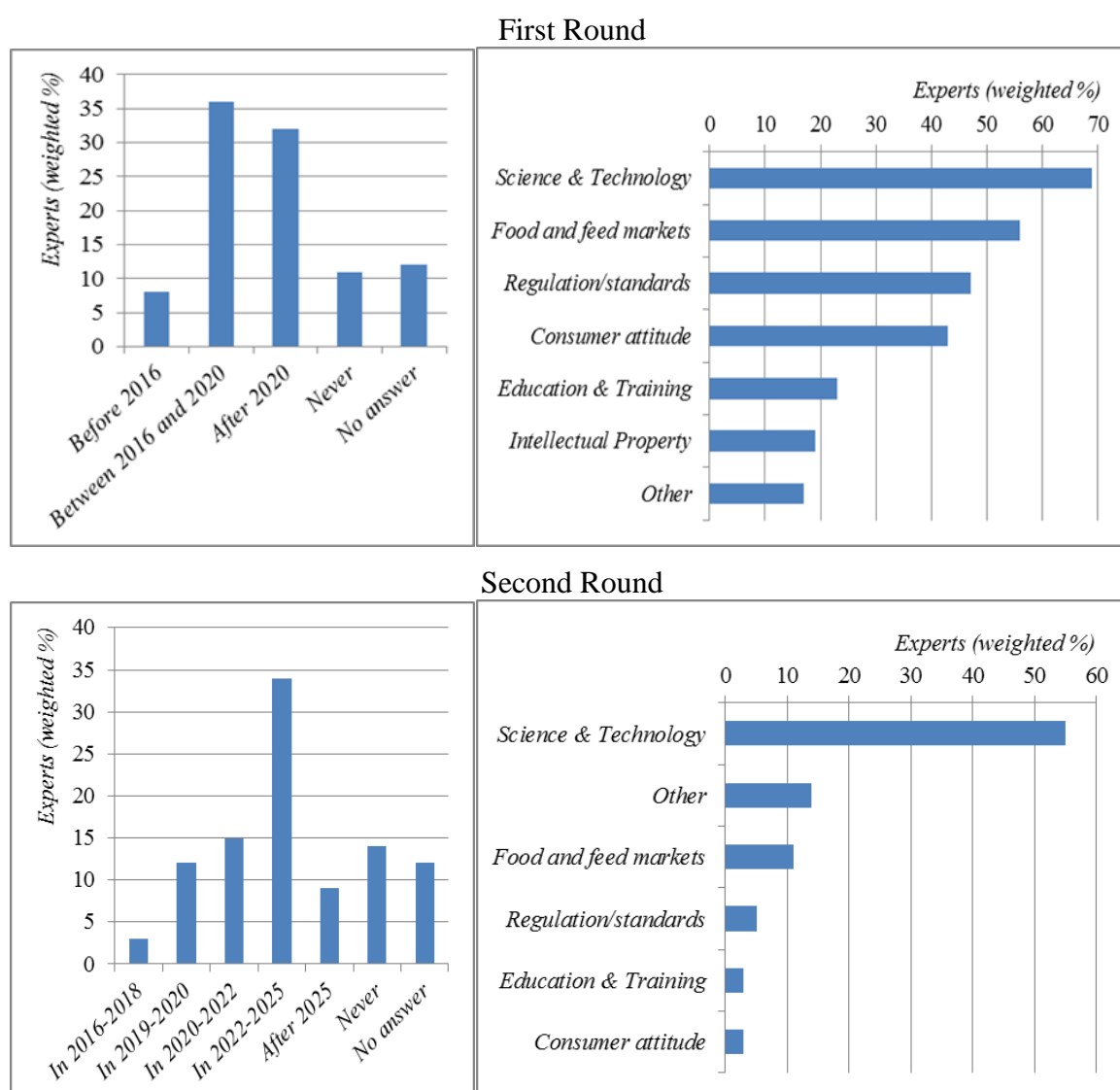
Figure 4 – First and second round Delphi results on future market position of EU firms



Note: Percentage of experts is weighted according to how familiar they are with the topic. We assigned a 50% weight to those indicating to be non-familiar, 100% to rather familiar and 150% to very familiar. Percentages are normalized in order to facilitate interpretation and comparison. Source: Enzing *et al.*, 2014. Reproduction is authorized provided the source is acknowledged.

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Figure 5 – First and second round Delphi results on on micro-algae-based products as substitutes for synthetic or natural sources.



Note: Percentage of experts is weighted according to how familiar they are with the topic. We assigned a 50% weight to those indicating to be non-familiar, 100% to rather familiar and 150% to very familiar. Percentages are normalized in order to facilitate interpretation and comparison. Source: Enzing *et al.*, 2014. Reproduction is authorized provided the source is acknowledged.

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Tab. 1 - Market figures of micro-algae based products

Microalgae-based product	Production volume (tons/year dry weight)	Number of producers	Production value (annual turnover, mio US \$)	Production value of alternative sources (annual turnover, mio US \$)
Whole dried micro-algae:				
<i>Spirulina</i>	5,000 (2012) ^(a)	15	40 (2005) ^(b)	No alternative
<i>Chlorella</i>	2,000 (2003) ^(a)	70	38 (2006) ^(c)	No alternative
High-value molecules:				
Astaxanthin	300 (2004) ^(a)	8	10 (2004) ^(c)	200 (2004) ^(b)
Phycobiliprotein (incl. phycocyanin)	(NA)	2	(NA)	50 (2004) ^(b)
Omega-3 fatty acids	240 (2003) ^(b)	4	300 (2004) ^(b)	14,390 (2009) ^(d)
Beta-Carotene	1,200 (2010) ^(c)	10	(NA)	285 (2012) ^(b)

Note: (a) Norsker *et al.*, 2011; (b) Milledge, 2012; (c) Spolaore *et al.*, 2006; (d) Ismail, 2010. In brackets the year for which the estimation was done. Source: Enzing *et al.*, 2014. Reproduction is authorized provided the source is acknowledged