



Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy

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The EU Bioeconomy Strategy aims to support the sustainable growth and development of the EU bio-based sectors while creating jobs, innovation and services. Despite the recognized potential of the algae biomass value chain, significant knowledge gaps still exist regarding the dimension, capability, organization and structure of the algae production in Europe. This study presents and analyses the results of a comprehensive mapping and detailed characterization of the algae production at the European scale, encompassing macroalgae, microalgae, and the cyanobacteria Spirulina. This work mapped 447 algae and Spirulina production units spread between 23 countries, which represents an important addition to the reported number of algae producing countries. More than 50% of these companies produce microalgae and/or Spirulina. Macroalgae production is still depending on harvesting from wild stocks (68% of the macroalgae producing units) but macroalgae aquaculture (land-based and at sea) is developing in several countries in Europe currently representing 32% of the macroalgae production units. France, Ireland, and Spain are the top 3 countries in number of macroalgae production units while Germany, Spain, and Italy stand for the top 3 for microalgae. Spirulina producers are predominantly located in France, Italy, Germany, and Spain. Algae and Spirulina biomass is directed primarily for food and food-related applications including the extraction of high-value products for food supplements and nutraceuticals. Algae production in Europe remains limited by a series of technological, regulatory and market-related barriers. Yet, the results of this study emphasize that the European algae sector has a considerable potential for sustainable development as long as the acknowledged economic, social and environmental challenges are addressed.

Keywords: Blue growth, seaweed, bioeconomy, biomass, production, algae

HIGHLIGHTS

- 447 algae and *Spirulina* spp. production units currently exist in Europe.
- A variety of species, production methods and commercial applications have been identified throughout the European countries.
- In Europe, the harvesting of wild stocks is the predominant production system for macroalgae (68% of the production units mapped). In the case of microalgae, photobioreactors are the main production method (71%) while for *Spirulina* spp., the open ponds prevail (83%).
- Upscaling of the production volumes and technological and market developments are key drivers to boost the growth of the sector in Europe.
- The European algae industry is a promising emerging sector of the EU Blue Bioeconomy with many data gaps still to be filled with, *inter alia*, studies like our research.

INTRODUCTION

Political Context

The current EU political priorities favor a transition to a sustainable economy balancing the growth of economic activities, the protection of natural resources and the needs of a growing world population. The EU Bioeconomy Strategy (adopted in 2012 and updated in 2018) (EC, 2018) aims at implementing a sustainable and circular bioeconomy throughout Europe. Its Action Plan encourages the strengthening and development of the EU bio-based sectors and the pursuit of sustainable food and production systems. In parallel, the EU Blue Growth Strategy (EC, 2012) fosters the creation of jobs in coastal areas and the sustainable growth of Europe's maritime economy and highlights aquaculture and blue biotechnology sectors among its priority targets.

The new European Commission's Green Deal targets priority areas where the algae production sector can provide a relevant contribution. These are, for example, the goals of the EU of becoming climate neutral by 2050, the protection of biodiversity (EC, 2020b), the development of a circular economy (EC, 2020a) and the contribution to the farm to fork strategy for sustainable food (EC, 2020c). Specific priorities of the Commissioner for Environment and Oceans are to boost the EU blue economy potential while pursuing the sustainability of fisheries and aquaculture production and their contribution to global food security and sustainability.

Environmental, Social and Economic Potential

Algae are key components of the marine environment and may play a significant role in addressing the EU strategical priorities. Algae provide many essential ecosystem services. Algae contribute significantly to the global primary production while also playing an important role in the uptake of dissolved nutrients from the surrounding environment, coastal defense from hazardous waves and potentially in carbon sequestration

(e.g., Dayton, 1985; Chapman, 1995; Steneck et al., 2002; Christie et al., 2009; Teagle et al., 2017). Macroalgae (or seaweeds) are also critical habitat-structuring species in coastal ecosystems (Reisewitz et al., 2006; Bertocci et al., 2015) whereas microalgae, as phytoplankton, constitute the basis of the marine and aquatic food-chain as the prime source of omega 3 fatty acids (Adarme-Vega et al., 2012).

Algae are used in an increasing number of commercial applications. Already widely established in Asia as a foodstuff, algae biomass is increasingly being incorporated in western diets directly for human consumption or used in a variety of food applications (Peteiro, 2018). Interest in including varying algae species in the European gastronomy has increased in recent years due to their nutritional and therapeutic properties and the search for more sustainable and natural food sources (Wells et al., 2016; Rioux et al., 2017; Mouritsen et al., 2019). Moreover, the genus *Arthrospira*, (commercially known and referred hereafter as *Spirulina*) (Vonshak and Tomaselli, 2002), is a cyanobacteria that has been traditionally used in Western human nutrition since the 1970s and is currently referred to as a "super food" given its nutritional properties (Jung et al., 2019). Microalgae are also widely used as food and nutritional supplements, with some species being important sources of specific components such as antioxidants, pigments, oils, and vitamins (Hemantkumar and Rahimbhai, 2019; Niccolai et al., 2019). Additionally, some seaweed species collected along the European coasts such as *Laminaria digitata*, *L. hyperborea*, *Ascophyllum nodosum*, and *Gelidium corneum* are used as feedstock for the extraction of food, pharmaceutical, biomedical or biotechnological grades of the hydrocolloids alginate and agar (Kraan, 2012; Peteiro, 2018). Algae biomass is also used in feed for aquaculture (Makkar et al., 2016; Wan et al., 2019) and recently explored as a feed supplement for cattle to improve weight gain while reducing enteric methane emissions (Machado et al., 2014; Roque et al., 2019; Kinley et al., 2020). Further uses include fertilizer and plant biostimulant applications as well as a source of high quality and high-value bioactive products for cosmetics and nutraceuticals (Thomas and Kim, 2013; Milledge et al., 2015; Chatterjee et al., 2017).

New applications of algae biomass are currently being explored for bioremediation and biomonitoring (Deng et al., 2007; Reis et al., 2016; Zeraatkar et al., 2016), biofuel production (Darda et al., 2019; Ravanal et al., 2019) and biopolymers (e.g., bioplastics) (Abdul Khalil et al., 2017; Zhang et al., 2019). Recent studies, some of which still at an early experimental phase, have emphasized the potential interest of these marine bioresources for innovative health products (Bogie et al., 2019; Kwon et al., 2020). Despite the growing interest and the potential of the algae production as an innovative sector within the EU bioeconomy, the current status of the algae industry in Europe remains largely unknown.

Robust and comprehensive information on the European algae sector is needed to adequately guide knowledge-based decisions and strategies supporting the socio-economic growth and environmental sustainability of the activity in Europe.

Available Knowledge

Data on the amount of algae biomass produced in Europe is reported under different EU level collection frameworks for catch and aquaculture statistics. This data is based on Member States and European Economic Area (EEA) member countries submissions (EC 762/2008, 2008; EC 216/2009, 2009; EC 217/2009, 2009; EC 218/2009, 2009; EU 2019/909, 2019) and centralized in Eurostat fisheries statistics and the European Commission's Joint Research Centre (JRC). At the global level, the Food and Agricultural Organization of the United Nations (FAO) also provides data for algae biomass (FAO, 2020). However, the available data are fragmented, incomplete and generally of low quality, which prevents a robust analysis of the sector. Due to the small volume of the algae production compared to other biomass sources, frequently there are no national legal obligations to report detailed data and the production is given as part of a total value or in an aggregated form. Additionally, data on microalgae production are almost non-existent and information is scattered and difficult to access (Vigani et al., 2015). A lack of accurate figures on the seaweed resource production has been identified as one of the main constraints to the development of the seaweed harvesting and farming industry in Europe (Mac Monagail et al., 2017) while an absence of knowledge on the production of microalgae has been recognized as a limiting factor for evaluating the potential of this sector in Europe (Vigani et al., 2015).

According to the available statistics, algae biomass production was increasing worldwide and reached 32.67 Mt [Fresh weight (FW)] in 2016 from which 0.57% of the volume was produced in Europe (including EU 27 + United Kingdom + Iceland + Norway) (Araújo et al., 2019a based on data from FAO). At the global level, algae biomass is mostly supplied by aquaculture (96.5% in 2016) while in Europe harvesting from wild stocks contributed to 98% of the total algae production volume in the same period (Araújo et al., 2019a). Significant knowledge gaps exist with this data.

In addition to the data on the production volumes by species, country and production method, other categories of information are relevant to understand the current landscape, the interplay of stakeholders and potential for growth of the algae sector in Europe. Successful stories from scattered industry players, including examples of research-industry partnerships, illustrate the potential of the sector for innovation in mitigating environmental pressures and bioprospecting and as a sustainable source for food (Blue Bioeconomy Forum, 2019). Simultaneously, challenges and constraints to the sector's development have also been repeatedly highlighted in different forums (Araújo et al., 2019b; Blue Bioeconomy Forum, 2019). Commonly referred to examples include regulatory barriers and the complexity of the administrative procedures and regulations, the still low consumer's awareness, the small market size, the sustainability of the production chain and the lack of credits for the environmental services provided by algae production. The access to good-quality data is also one of the gaps listed (Araújo et al., 2019b).

Objectives of the Study

This paper presents the findings from different collaborative initiatives aiming at increasing the information and knowledge on the algae sector in Europe. These findings are based on the outcomes of a workshop and the comprehensive collection of information from different sources and stakeholders. Based on the analysis of the information compiled, our research provides a comprehensive description of the algae production sector at the European level which is, to the best of our knowledge, not available elsewhere. The resulting analysis is based on original data and describes the main characteristics and geographical distribution of the algae biomass production units. The compiled information fills existing knowledge gaps in order to support the development and implementation of evidence-based initiatives and strategies for a European-wide development of the sector.

MATERIALS AND METHODS

For the purpose of this study the term "algae" includes macroalgae and microalgae. The production of *Spirulina* will also be addressed, given that this group of organisms is frequently considered, from the industry and consumer perspective, under similar frameworks as "algae" (e.g., CEN/TC454, 2020).

Identification of Constraints and Ways Forward

A workshop to discuss the gaps and priorities of the knowledge on algae biomass in Europe was organized by JRC in collaboration with FAO and The European Cooperation in Science and Technology (COST) with the participation of stakeholders from the research, data collection and management, industry and policy sectors (**Figure 1**). Twenty-four attendees were divided into four discussion groups, designed to balance the expertise and working field of participants. The same four different questions regarding algae biomass data reporting were discussed by each of the 4 groups (**Figure 1**). The common answers to 4 and 3 of the discussion groups are presented (**Table 1**). The participants identified the harmonization of data reporting formats and content as the most important action to increase the quality of data on algae biomass. The availability of information about screening and characterization of new species and the support to the expansion of the EU market were identified as priority needs for the sector (**Table 1**).

Collection of Data

The discussions held during the workshop reinforced the need to collect additional and comprehensive information about the algae production industry in Europe (**Table 1**).

To fulfill this knowledge gap, the algae producers in Europe (EU 27 + United Kingdom + EEA countries + Switzerland) were mapped and different categories of information collected. Only companies with production units in Europe were considered. Algae companies were considered as producers

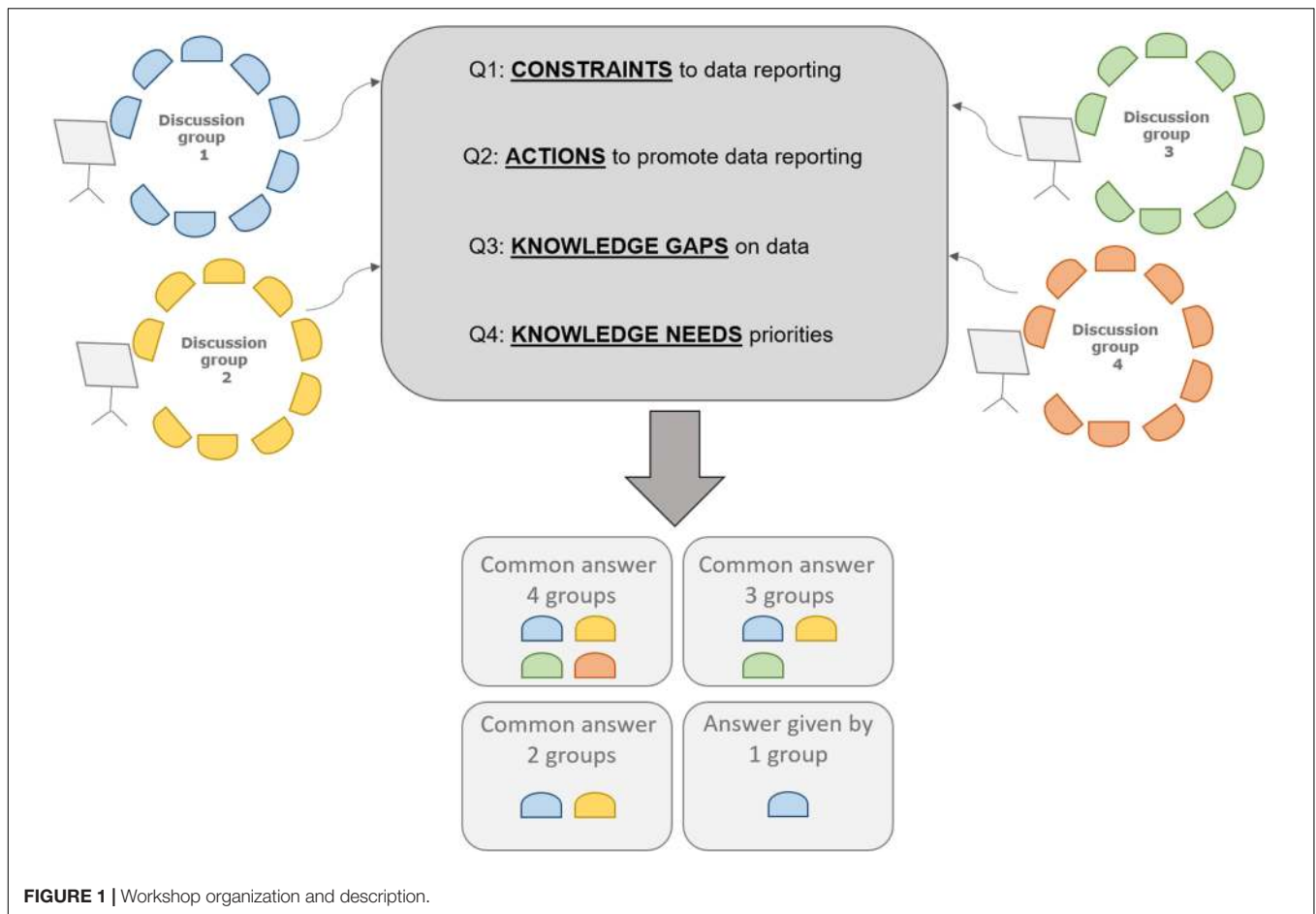


FIGURE 1 | Workshop organization and description.

TABLE 1 | Results of the workshop discussion rounds: answers common to 4 and 3 of the groups.

Which are the main CONSTRAINTS to data reporting	
Common answer to 4 groups	Common answer to 3 groups
Data confidentiality	Inadequacy of the reporting format to the algae sector
Which ACTIONS are more relevant to increase the effectiveness of the data reporting	
Common answer to 4 groups	Common answer to 3 groups
Distribution of the questionnaire and analysis of data by national association reference center regionally represented Harmonization of reporting rules with clearly defined guidelines on what and how to report	Clear, simple and accurate questionnaire format
Which are the main KNOWLEDGE GAPS on biomass production data	
Common answer to 4 groups	Common answer to 3 groups
Lack of reporting standardization: species names, cultivation methods, biomass metrics (wet/dry), water content	Information on genetics and biomass composition
Which are the main PRIORITIES in KNOWLEDGE NEEDS on biomass production and uses	
Common answer to 4 groups	Common answer to 3 groups
New species (also local species) profile: new uses, food safety, domestication protocols, whole value chain	Criteria for quality to promote regulation and increase the EU market (versus import from Asia)

even if additionally carrying out other activities (e.g., biomass processing or research).

For the European macro- and microalgae producers the list was initially based on the information provided by the European Algae Biomass Association (EABA), which was revised and further developed with data and information collected from different sources. At the first stage, information was gathered from websites, reports, meetings with stakeholders and expert consultation. The information from the identified companies was verified through desktop research into their websites or through direct contact via email or phone. Further information on their operational status, location of the production facilities and production methods were also requested. From this exercise, a first list of producing companies was obtained with three categories of data: Level 1: Companies that confirmed the information through contact; Level 2: Companies that did not reply to the contact but with web information of sufficient quality to be included in the database; Level 3: Companies that did not reply to the contact and for which the information retrieved from the website was not of sufficient quality to be included in the database. A second round of web research was conducted and 25 of the investigated companies were identified as “not biomass producers.” A consultation involving experts from 11 algae producing countries in Europe was carried out to review the identified list of producers critically. A final list of 225 producers was obtained and the companies on this list contacted to participate in an online survey collecting information on the following topics: geographical location of the production units, organism produced (macroalgae or microalgae), production method, year of establishment of the company, identity of the species produced and commercial uses of the produced biomass. A response rate of 40% was obtained in this survey. For the remaining companies (Level 2 companies) the information was obtained from the web or through direct contact with individual stakeholders. The analysis presented in this study corresponds to the information collected from Level 1 and Level 2 companies which is equivalent to 90% of the companies identified as algae biomass producers in Europe.

For *Spirulina*, the information was collected from the lists of EABA and the Fédération des Spiruliniers de France. The combined list was completed with information coming from the JRC microalgae database (several companies produce both organisms), the web and consultations with stakeholders.

This data was organized in a database, stored by JRC and used as underlying information source for the analyses conducted on the current status of the algae production sector in Europe.

Data Visualization

The most relevant data from the JRC database were visualized and made publicly available through two platforms:

- An algae industry directory hosted by the European Marine Observation and Data Network (EMODnet) Human Activities Portal¹: algae companies are displayed in the

¹<https://www.emodnet-humanactivities.eu/view-data.php>

EMODnet mapping based on the information on location of the production unit, group of organism and species produced, and production method.

- Country dashboards: as part of the efforts to gather, synthesize and disseminate the large and scattered information on the bioeconomy, the European Commission’s Knowledge Centre for Bioeconomy is producing and populating the bioeconomy country dashboard with bioeconomy relevant data and information at the national level. Thanks to the JRC Algae Database, the dashboard now also shows data on the European algae sector².

RESULTS AND DISCUSSION: CURRENT STATUS OF THE ALGAE PRODUCTION SECTOR IN EUROPE

According to the results of this study, the European algae sector amounts to 225 macroalgae (67%) and microalgae (33%) producing companies. Additionally, 222 *Spirulina* producers were identified, 15% of which are also microalgae producers (and included in the microalgae accounting), spread between 23 countries (Figures 2, 3). Spain, France and Ireland support the largest number of macro- and microalgae companies followed by Norway, the United Kingdom, Germany and Portugal (Figures 2, 4). The largest seaweed biomass volumes in Europe are produced by Norway, France and Ireland (Araújo et al., 2019a).

Information about the starting year of production activities was retrieved for 215 companies. When solely considering the new companies starting the activity in the last decade an increase of 150% in the number of new algae producing companies was registered and 10 of the current companies were already operating before 1980 (Figure 5). This trend evidences the existing interest in the development of this sector in Europe and demonstrates the temporal stability of some of the companies. For less than 10% of these companies the algae production is, however, not the main business activity.

The increasing temporal trend in the number of new algae production companies established since 1926 shows both the dynamics and the potential for growth of the sector. This trend needs to be critically analyzed since many other companies have closed or diverted their activities over the years.

Different studies have highlighted the potential of algae biomass production as an economically sustainable activity in the European bio-based industry landscape (Buschmann et al., 2017; Hasselström et al., 2018). Several constraints, however, still limit the sector expansion, the primary constraints being, but not limited to, the small market size for algae commodities in Europe, the variability in the annual biomass supply, the current state of technological development in the production and processing of biomass.

²https://knowledge4policy.ec.europa.eu/visualisation/bioeconomy-different-countries_en#algae_prod_plants

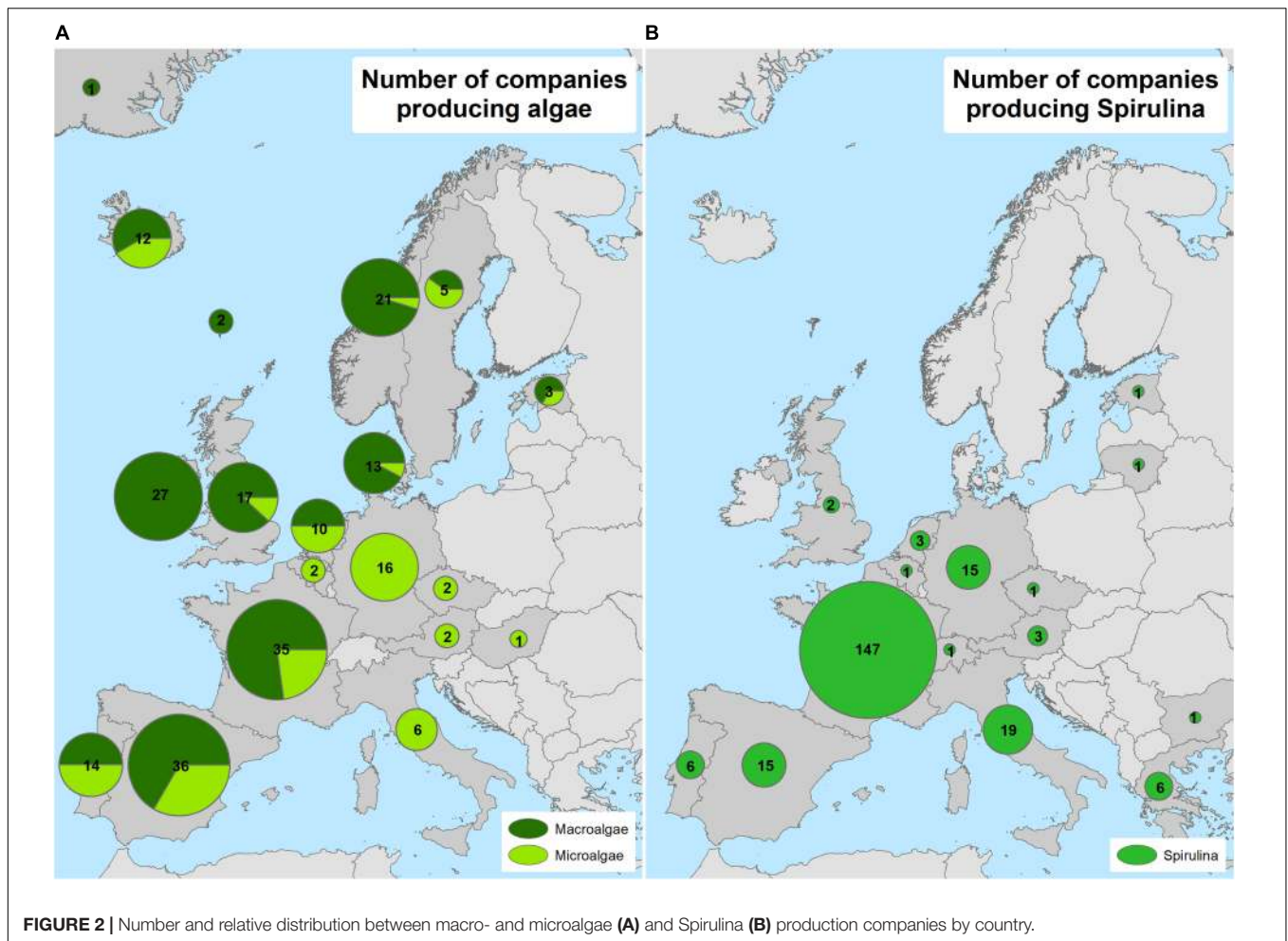


FIGURE 2 | Number and relative distribution between macro- and microalgae (A) and Spirulina (B) production companies by country.

The complexity and/or inexistence of some EU and national regulations in aspects such as cultivation licenses as well as definition of threshold values and measuring variables for harmful metal in food and the lack of harmonization of guidelines for organic certification between countries represent also a burden (Hasselström et al., 2018; Araújo et al., 2019b; Barbier et al., 2020).

MACROALGAE

Spain, France, and Ireland are the countries in Europe with the largest number of macroalgae companies (more than 20 producers each) (Figure 2). Macroalgae production is being developed in a total of 13 countries with Norway, the United Kingdom and Denmark having more than 10 production units. The activities connected to the seaweed production represent an essential livelihood and source of income for some coastal and rural communities and are part of a cultural heritage that is important to preserve (Frangoudes, 2011; Mac Monagail et al., 2017). In some European coastal areas, seaweeds were traditionally gathered by coastal communities for centuries for food, cattle feed and fertilizer and from around the middle of the 20th

century, were also used for hydrocolloids extraction (García Tasende and Rodríguez González, 2003; Frangoudes, 2011; Guiry and Morrisson, 2013; Mouritsen et al., 2013; García Tasende and Peteiro, 2015; Peteiro, 2018). Currently, the market for seaweed biomass is much more diversified and the technologies for biomass gathering more advanced. Yet, in some European regions, seaweed gathering still represents a family activity passed on for generations (Alban et al., 2011).

Production Methods

Seaweed production in Europe (considering both harvesting from wild stocks and aquaculture) is primarily concentrated in the Atlantic region with very few companies producing macroalgae in the Mediterranean area (Figure 3A). This is related to the geographical distribution, the larger extension of the intertidal area and a higher abundance and dimension of seaweed species traditionally exploited at an industrial scale on the Atlantic coasts. These factors historically facilitated the expansion of an algae industry based on the mechanical and manual harvesting of wild resources. Some companies are cultivating species that are native to the Mediterranean (e.g., *Ulva* sp., *Gracilaria* sp.)

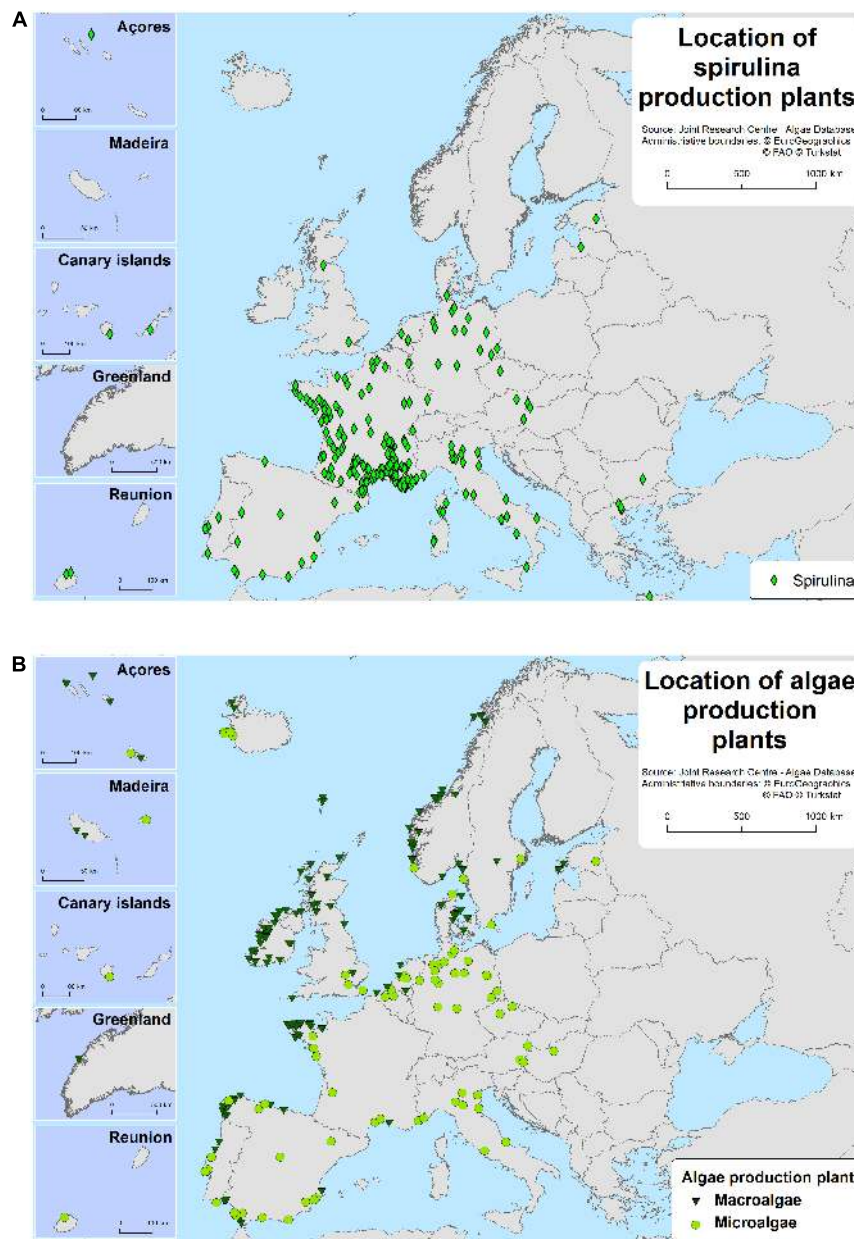


FIGURE 3 | Location of the algae (A) and Spirulina (B) production plants in Europe.

but these units correspond to a minority of the European production (Figure 3A). Some initiatives at the European and regional level are now trying to identify the factors limiting the expansion of this activity in the Mediterranean and discussing measures that could promote the cultivation of seaweeds in this area.

(a) Harvesting From Wild Stocks

As anticipated by the data on production volumes (Araújo et al., 2019a), harvesting from wild stocks is the primary production method for macroalgae in Europe, and this has not changed appreciably over the past two decades (Araújo

et al., 2019a). Harvesting is the production technology used by 68% of the macroalgae production units (excluding pilot plants) covering 11 European countries (Figures 4, 6). Among these, 85% of the producers harvest the biomass by hand (Figure 6). Mechanical harvesting is usually carried out by companies running a fleet of vessels. Hence, mechanical harvesting, although representing only 15% of the production units (Figure 6), presents a greater potential in terms of biomass removal compared to manual harvesting. Spain, France and Ireland are the countries with the highest number of seaweed harvesting companies (Figure 4). With exception of Denmark, Norway, and Netherlands, harvesting (either

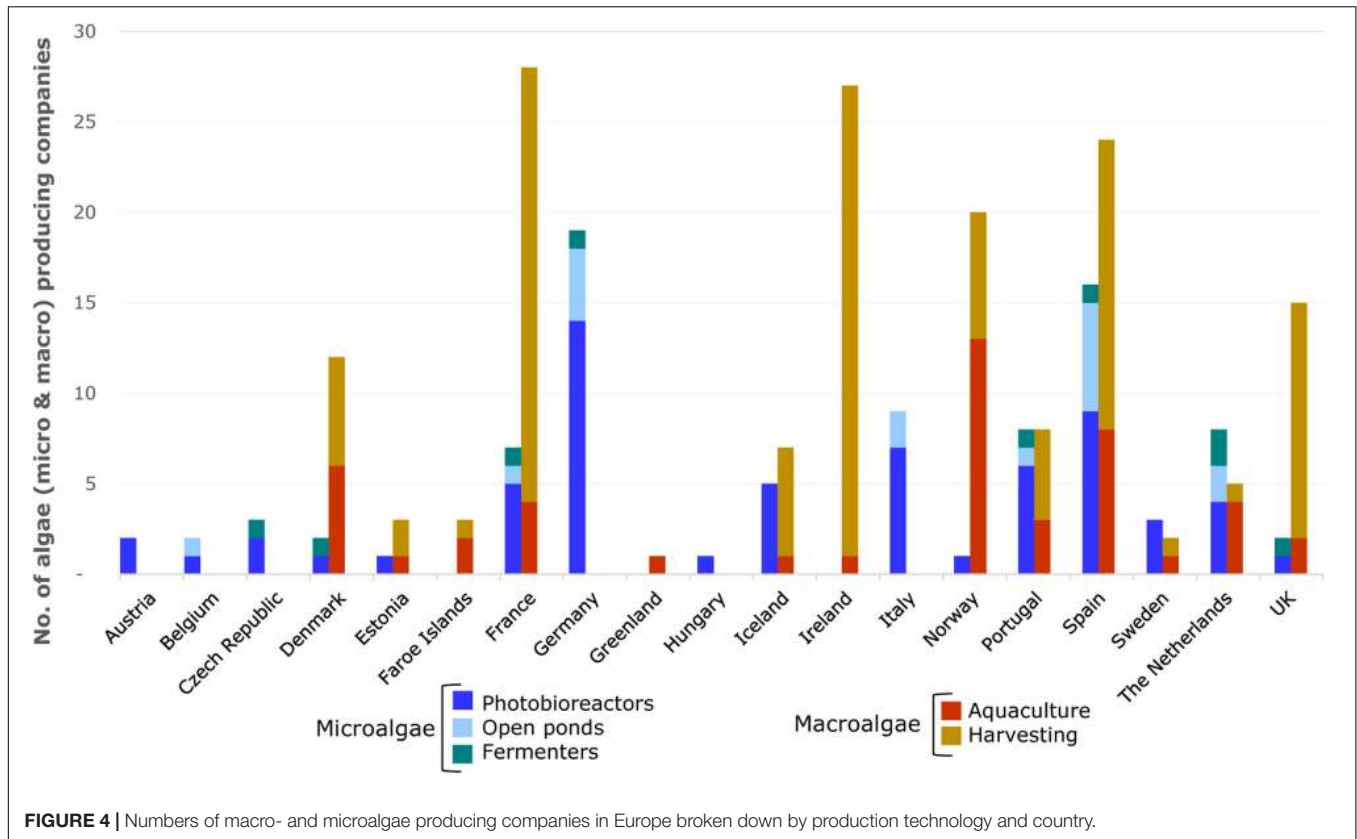


FIGURE 4 | Numbers of macro- and microalgae producing companies in Europe broken down by production technology and country.

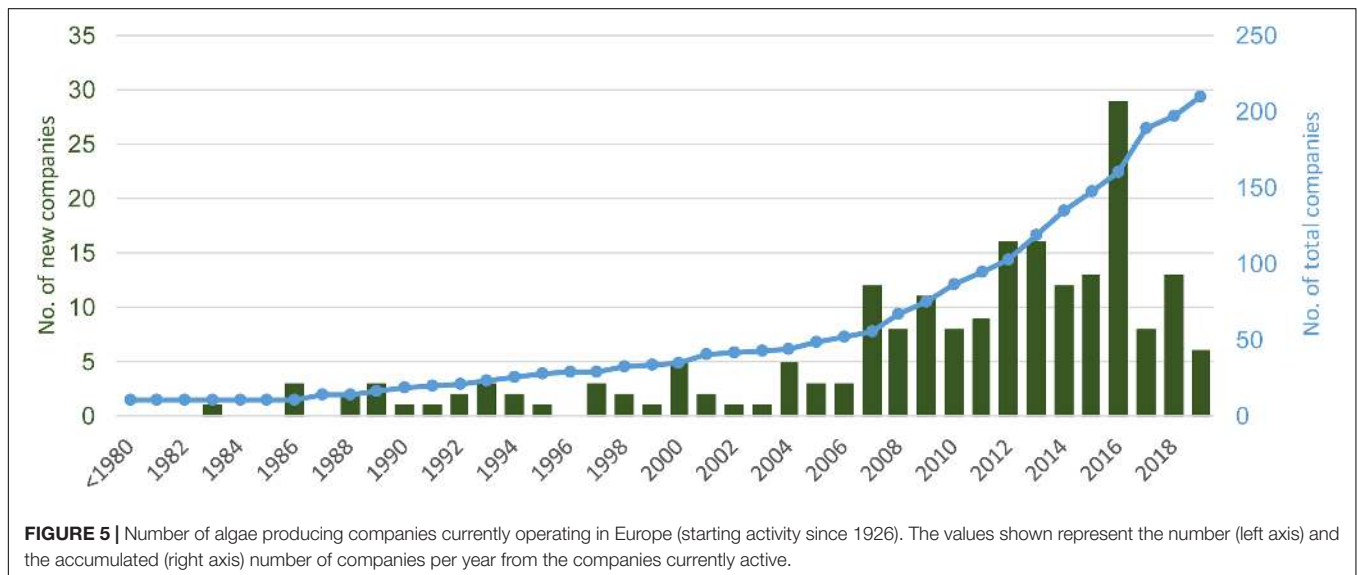
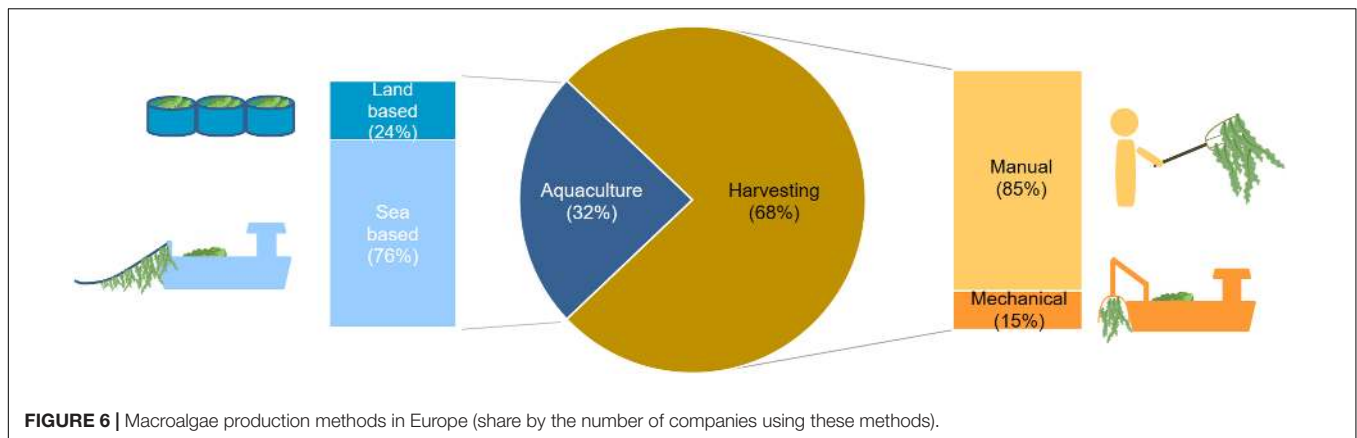


FIGURE 5 | Number of algae producing companies currently operating in Europe (starting activity since 1926). The values shown represent the number (left axis) and the accumulated (right axis) number of companies per year from the companies currently active.

manual or mechanical) is the dominant method for all the macroalgae producing countries when considering the number of production units (Figure 4). Countries along the Atlantic coastline, like Ireland and Spain, have a long tradition for hand harvesting of seaweeds (García Tasende and Rodríguez González, 2003; García Tasende and Peteiro, 2015; Mac Monagail and Morrison, 2020). Although used by only a minority of the harvesting companies in Europe, mechanical

harvesting potentially corresponds to higher incomes and removal of larger algal volumes (Alban et al., 2004). The species collected by each harvesting method differ with only a few species being harvested mechanically (Frangoudes, 2011; Rebours et al., 2014).

In France, seaweed biomass is harvested by hand and mechanically from boats (using scoubidou devices or large rake-like implements, depending on the target species)



(Davoult et al., 2011; Frangoudes, 2011). In Brittany, the most critical seaweed production region in France (Figure 3A), kelp species harvesting is traditionally carried out by a fleet of small vessels operating seasonally. *Laminaria digitata* is traditionally harvested from May to September following quotas established by management plans. These plans are established in accordance to the available annual biomass and regulate the number of vessels by harvesting area, the starting period of the harvesting season and the number of harvesting days per week. Similarly, the harvesting of *L. hyperborea* is also managed by quotas established for areas which open every 3 years. These areas are harvested between the beginning of September and mid-May, but the autumn biomass removals represent 75 to 80% of the total annual volume of harvested algae biomass. Recently all the fleet was equipped with Vessel Monitoring Systems (VMS) which will improve harvesting management practices. During the winter, some vessels target shellfish, but the main activity of this fleet is kelp harvesting (Alban et al., 2011). Maerl was harvested mechanically in many parts of Brittany using a “sablier” suction dredge (Mac Monagail and Morrison, 2020), but this activity is banned since 2011 in France. In large parts of the coast, particularly in Brittany, seaweed is harvested by hand (a traditional economic activity running for more than 300 years). *Fucus* sp., *A. nodosum*, and *Chondrus crispus* are the most harvested species followed by an extensive list of edible species e.g., *Palmaria palmata*, *Porphyra* sp., *Ulva* sp. or *Himanthalia elongata*. The harvesting of these edible species is a recent activity but the economic importance of this sector is increasing over time.

On the Atlantic coast of Spain, seaweeds with economic interest [mainly edible species such as *Undaria pinnatifida*, *L. ochroleuca*, *Ulva* spp., *H. elongata* but also *C. crispus*, and *Mastocarpus stellatus* which are used for the extraction of carrageenans (García Tasende et al., 2012, 2013)] are harvested manually from shore, on foot, during low tides or from vessels by diving (García Tasende and Rodríguez González, 2003; García Tasende and Peteiro, 2015). The agarophyte *G. corneum*, exploited on the Cantabrian coast (Asturias, Cantabria, and Basque Country), is traditionally collected from beach-cast, and more recently by harvesting using hand-plucking or cutting. Beach-cast *Gelidium* biomass is harvested with the traditional use

of rakes and forks or more recently with buck rakes operated with tractor, while the harvesting of the subtidal *Gelidium* beds is carried out by diving from a vessel (Juanes and Sosa, 1998).

Norway is the number one seaweed biomass producer (in terms of volume) in Europe (Araújo et al., 2019a) mostly by mechanical harvest of kelp and Fucales. A limited number of other species such as *Ulva* spp., *Porphyra* spp., and *P. palmata* are also handpicked for high-end users such as restaurants in the recent decades. The main volumes are harvested with the use of seaweed trawlers and mechanical cutting, an activity that started already in the 1960s and targets two main species: *L. hyperborea* and *A. nodosum* (Vea and Ask, 2011; Mac Monagail et al., 2017). The same two species are harvested by hand in Ireland using traditional techniques that differ among regions (Mac Monagail and Morrison, 2020).

In Ireland, new harvesting methods have been introduced since 2015 in particular the use of rakes from boats for *A. nodosum* harvesting and the use of mechanical harvesters for removing kelp biomass (Mac Monagail and Morrison, 2020).

In Iceland mechanical harvesters equipped with adjustable rotating cutting blades are used to collect *A. nodosum* (Mac Monagail and Morrison, 2020) while *Lithothamnion* sp. is harvested using a vessel that pumps the algae onto the shore where it is then further processed and dried.

In countries like Portugal or Estonia, few companies harvest seaweeds. The harvested biomass is restricted to a small diversity of species (*Gelidium* sp. in Portugal and *Furcellaria lumbricalis* in Estonia) which is used as a feedstock for hydrocolloid production.

In the United Kingdom and Denmark manual harvesting is also the primary harvesting method, although mechanical harvesting of *Ulva* sp. green tides is being developed.

Harvesting of seaweed wild stocks faces the challenge of balancing the socio-economic and environmental sustainability of the activity. The sustainability of harvesting practices has been under debate in several regions (Callaway, 2015; García Tasende and Peteiro, 2015; Marine Scotland Directorate, 2016; Mac Monagail et al., 2017; Burrows et al., 2018). Strict management plans for harvested resources are frequently put in place by the regional authorities, harvesters' associations or harvesting companies (García Tasende and Rodríguez González, 2003; Frangoudes, 2011). The recent trend showing a reduction in

the abundance of some of the harvested species in some coastal areas (Araújo et al., 2016; Krumhansl et al., 2016; Filbee-Dexter and Wernberg, 2018; Casado-Amezúa et al., 2019; Wilson et al., 2019) raises additional concerns on the sustainability of harvesting from wild stocks, which potentially has an impact on the natural communities (Lorentsen et al., 2010; Davoult et al., 2011). Management plans and monitoring programs should take into consideration the harvesting methods, species identity and geographical location of the harvested resources (García Tasende and Peteiro, 2015; Burrows et al., 2018; Lotze et al., 2019).

(b) Aquaculture

Aquaculture production of macroalgae, presently ongoing in 13 European countries, is at an early stage of development in Europe in terms of production volumes and number of production units (Figure 4). According to the official statistics, seaweed aquaculture production contributes to less than 1% of the total European seaweed biomass production (Araújo et al., 2019a), accounting in this study for 32% of the mapped macroalgae production units (Figure 6). Most of the production units are located at sea (offshore or in coastal waters) with only 24% of the companies conducting land-based activities (Figure 6).

Seaweed aquaculture is seen as a possible way to meet the increasing demand from the processing industry for traceable, high quality and predictable yields of biomass. Furthermore, it is widely recognized that a transition from wild stock seaweed harvesting to aquaculture is needed to meet the growing demand while avoiding the overexploitation of wild seaweed resources. Moreover, there has been increasing interest in environmentally friendly farming practices where macroalgae will play a key role in the emerging development of integrated multi-trophic aquaculture (IMTA), which is currently promoted at both European and national level (Alexander et al., 2016; Buck et al., 2018; Kleitou et al., 2018). In Europe, Norway is the country with the highest number of seaweed aquaculture companies (Figure 4). This is a result of the recent Norwegian strategy encouraging research institutions, industries and public authorities to develop a bioeconomy based on the production and processing of cultivated seaweeds (Stévant et al., 2017). The first licenses for seaweed cultivation at sea in Norway were granted in 2014. In 2019 the surface allocated to seaweed cultivation was 834 ha, which corresponds to a production potential of approximately 48,000 tons (FW), with a registered production of 111 tons for a value of about EUR 0.43 million (Directorate of Fisheries, 2020). The estimated potential has not been reached yet since only part of the companies holding a permit are currently in operation and most have still reduced production capacity (Broch et al., 2019). Although a large-scale cultivation is not yet a reality, the Norwegian coast has the optimal conditions to expand further the area and location of the cultivation sites (Stévant et al., 2017).

Other countries, like Denmark, currently have an equal share of aquaculture and harvesting companies (Figure 4), with commercial companies dedicated to large-scale kelp production as part of IMTA since 2012 (Marinho et al., 2015).

In countries like France, Spain, and Portugal some aquaculture companies are already established at a fully commercial scale with sea-based (coastal) or land-based production facilities. In Spain,

the development of commercial-scale aquaculture of edible kelp species has been receiving increasing interest since the beginning of the 2000s (Peteiro et al., 2016 and references therein). This attention boosted the development of commercial sea farming initiatives for two seaweed species: *Saccharina latissima*, and *U. pinnatifida*, the latter being banned by the national environmental regulation on alien invasive species. Currently there are some licenses granted (at least four authorizations) for the commercial cultivation of *S. latissima* at sea- and land-based systems. Although the number of licenses is still small, it is expected that seaweed aquaculture will grow significantly during the coming years, particularly the cultivation of species with high demand and high commercial value and for which the extraction from wild stocks is not currently authorized due to environmental protective measures (e.g., for *S. latissima* and *P. palmata*) or the low availability of wild biomass (e.g., *Porphyra sensu lato*). Other seaweed species such as *Ulva* spp. and *Gracilaria/Gracilariopsis* spp. are also currently cultivated on land-based tanks. Other countries with cultivation facilities are Estonia, Faroe Islands, Iceland, Ireland, Sweden, the Netherlands, and the United Kingdom (Figure 4).

Different cultivation techniques are in use depending on the target species and available conditions. Each cultivation technology has its own advantages and challenges (Barbier et al., 2019).

Land-based cultivation involves higher availability of land space, and it is associated with high infrastructural and operational costs. It is the most suitable method for certain species and for high-value applications (e.g., functional products for human consumption, cosmetics, and pharmaceuticals). Land-based cultivation offers the possibility of producing biomass in a more controlled environment obtaining a more consistent supply throughout the year and thus better control of the biomass quality, standardization, traceability, security, and composition (Hafting et al., 2012, 2015; Pereira et al., 2013; Barbier et al., 2019).

Sea-based cultivation, which presents a higher potential for scaling up the production volumes, is the dominating production method for kelp species. However, it results in more variable yields, less control of the quality of the biomass (Titlyanov and Titlyanova, 2010), higher risks of diseases and pests (Ward et al., 2020) and vulnerability to environmental conditions (e.g., major storms, torrential rains) (Peteiro et al., 2014). Adequate site-selection of the production facilities to guarantee the suitable environmental conditions for biomass growth and cultivation is also challenging (Bruhn et al., 2016; Peteiro et al., 2016; Barbier et al., 2019; Visch et al., 2020a). Most of the current sea-based seaweed cultivation systems in the world are located in coastal areas and shallow oceans (Buschmann et al., 2017).

Offshore aquaculture is estimated to have the advantage of reducing conflicts in the use of space and consequently has a higher potential for upscaling of the production facilities (Barbier et al., 2019). In some regions, offshore cultivation also gives a higher guarantee of stable and suitable environmental conditions (Broch et al., 2019). The main challenge to this production method is the need to develop cultivation methods and innovative solutions to withstand the forces of offshore seas, to reduce the currently high infrastructural and logistics

costs associated with offshore operations and to increase the biomass yields (Buck and Buchholz, 2004; Peteiro et al., 2014; Zuniga-Jara et al., 2016; Bak et al., 2018; Buck et al., 2018). At present, innovative projects seek for the development of new techniques that may increase the profitability of this production method (Bak et al., 2018) and for the design of multifunctional structures combining other economic activities, for example wind farms with seaweed aquaculture facilities (Jansen et al., 2016; Buck and Grote, 2018; van den Burg et al., 2020). Offshore production still represents a minority of the aquaculture units in Europe, but cultivation systems adapted to highly exposed seas have been developed and tested for several years at the Faroe Islands (Bak et al., 2018). Increased modeling complexity and accuracy will support aquaculture development. Recent modeling studies show spatial variations in the cultivation potential of *S. latissima* in Norway (Broch et al., 2019), the role of environmental nutrient concentrations in the biochemical composition of algae biomass (van der Molen et al., 2018) and the growth dynamics of *S. latissima* with variable environmental parameters (Venolia et al., 2020).

Integrated Multi-Trophic Aquaculture (IMTA) systems, already used by approximately 10% of the European aquaculture companies, may represent an opportunity to increase the economic and environmental sustainability of the production of all the involved cultures. The IMTA concept is based on the co-cultivation of species from different trophic levels (2 or more) (Figure 7) and is regarded as a potential mitigation approach, reducing the nutrients and organic matter inputs from finfish aquaculture (e.g., Chopin et al., 2001; Neori et al., 2004; Troell et al., 2009; Buck et al., 2018). In some coastal areas, such as Norway, the ubiquitous presence of fish aquaculture units is regarded as an opportunity to develop a production system based on the co-cultivation of fish and seaweed, the latter benefiting from the nutrient-enriched effluent waters from fish aquaculture (e.g., Handá et al., 2013; Marinho et al., 2015; Stévant et al., 2017) (see Figure 7). This is similar to other aquaculture practices in north-western Spain (Galicia) where commercial kelp farming is developed in culture areas with a high density of mussel floating rafts (Peteiro and Freire, 2013; Peteiro et al., 2016).

Current efforts to upscale the industrial production of seaweeds have focused on implementing efficient farming strategies and developing technologies to optimize the cultivar production and deployment, biomass harvest and crop handling logistics (Peteiro et al., 2019; Stévant, 2019; Goecke et al., 2020). Innovation in automation of processes during seeding, biomass monitoring, harvesting and processing is needed to improve economic sustainability. Recent developments in this field include automated evaluation of biomass density in land-based systems through spectral reflectance imagery (Praeger et al., 2020) or the use of intelligent management systems in IMTA by using underwater drones for biomass monitoring at sea (IMPAQT project³). The development of the sector will also greatly depend on the increasing demand for certain species and the expansion of specific market segments. Production of species currently with high demand but low biomass supply

(e.g., *P. palmata*, *Porphyra* spp., *Ulva* spp.) needs to be increased (Barbier et al., 2019).

The aquaculture sector still faces negative public perception related to the management of space and the social acceptability of the aquaculture practices and products. Several additional challenges also need to be solved: control of pests, diseases, genetic contamination, selection of strains, fundamental knowledge on different aspects of seaweed biology and physiology, threats from climate change and herbivory as well as an understanding of the impact of aquaculture in the surrounding ecosystems (Buschmann et al., 2017; Stévant et al., 2017; Campbell et al., 2019). Recently, the environmental risks associated with seaweed farming have been assessed on various ways in different environments (Cabral et al., 2016; de Carvalho et al., 2017; Walls et al., 2017; Hasselström et al., 2018; Visch et al., 2020b). Biomass production from seaweeds at the global level is still far from being comparable to land-based agriculture. However, recent exploratory studies have shown promising resource efficiencies from aquaculture production (Taelman et al., 2015), which highlights the potential of seaweed aquaculture to contribute to solving societal challenges such as climate change (Duarte et al., 2017; Philis et al., 2018), eutrophication of coastal waters (Duarte and Krause-Jensen, 2018) and well-being of local communities including women empowerment (Rebours et al., 2014). Given the limitations to the increase in food production from agricultural systems, aquaculture contribution to global food security is expected to progressively increase. This development will entail additional challenges to the interplay of the aquaculture's multiple sustainability dimensions (Loureiro et al., 2015; Cottier-Cook et al., 2016; Buschmann et al., 2017).

Species Produced

Although there are many seaweed species distributed in European waters [estimated to be around 1700 species (Costello et al., 2006)], only a small part of these are commercially exploited (Mac Monagail and Morrison, 2020) and, for many of them, only in some coastal areas.

(a) Aquaculture

Seaweed aquaculture production is currently limited to a reduced number of species from the total which are commercially exploited in Europe. From the available data, the seaweed volumes produced by aquaculture represent a minor fraction of the wild seaweed stock harvested. Figure 8 shows the share in the number of companies producing each species in Europe. For some of the species the combined yearly production volumes at the European level are presented (when available). *Saccharina latissima* is the most produced species by aquaculture (both considering production volume and number of companies) with an estimated annual production in Europe of 376 tons (FW) (Figure 8). This species has been the main target in the large-scale sea-based cultivation systems in Europe due to several reasons: broad geographical distribution (Muller et al., 2009), early availability of kelp production protocols (Edwards and Watson, 2011; Yarish et al., 2017; Forbord et al., 2018; Peteiro, 2018), the potential for higher biomass yields (Kraan, 2010;

³<https://impaqtproject.eu/>

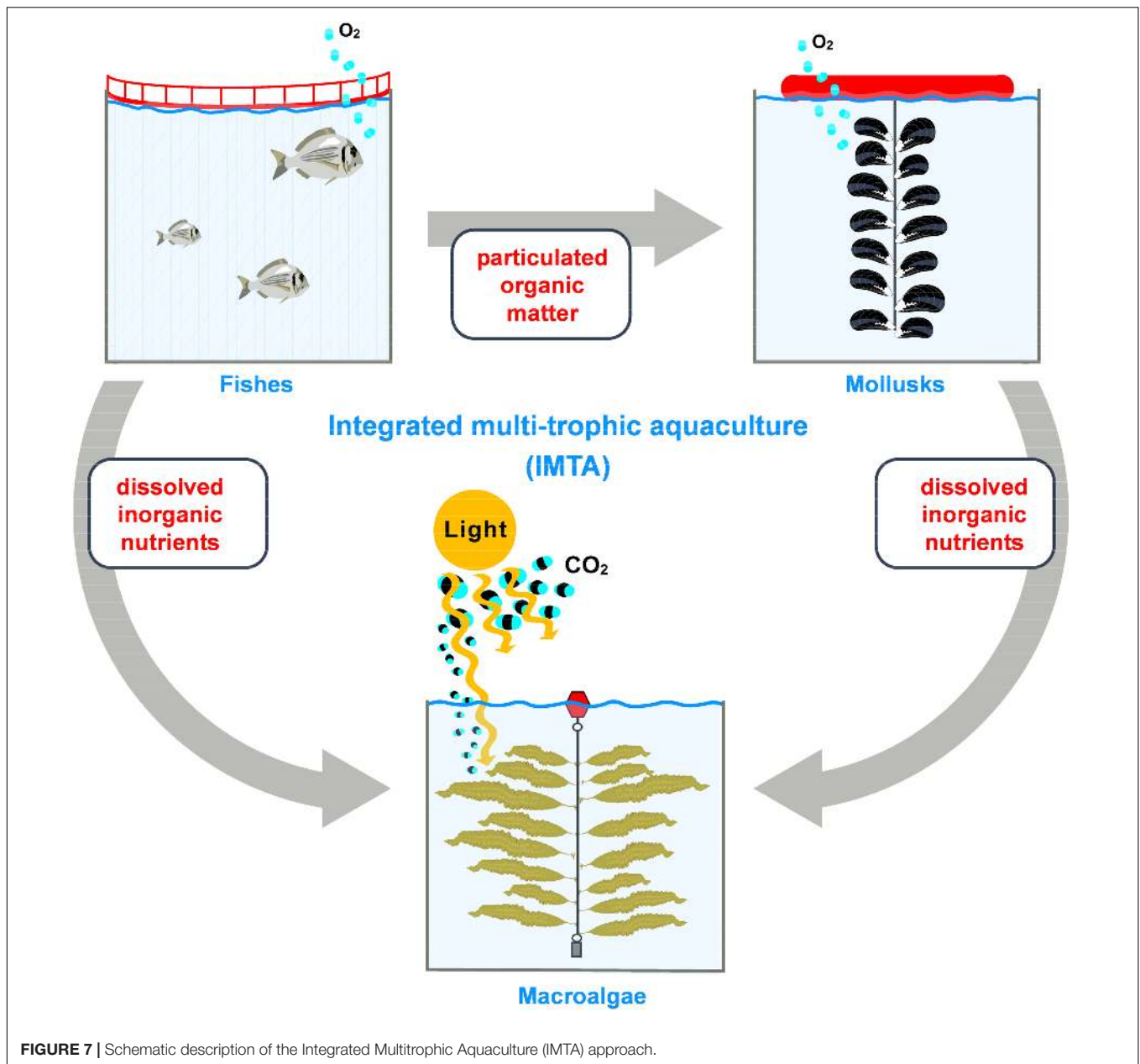


FIGURE 7 | Schematic description of the Integrated Multitrophic Aquaculture (IMTA) approach.

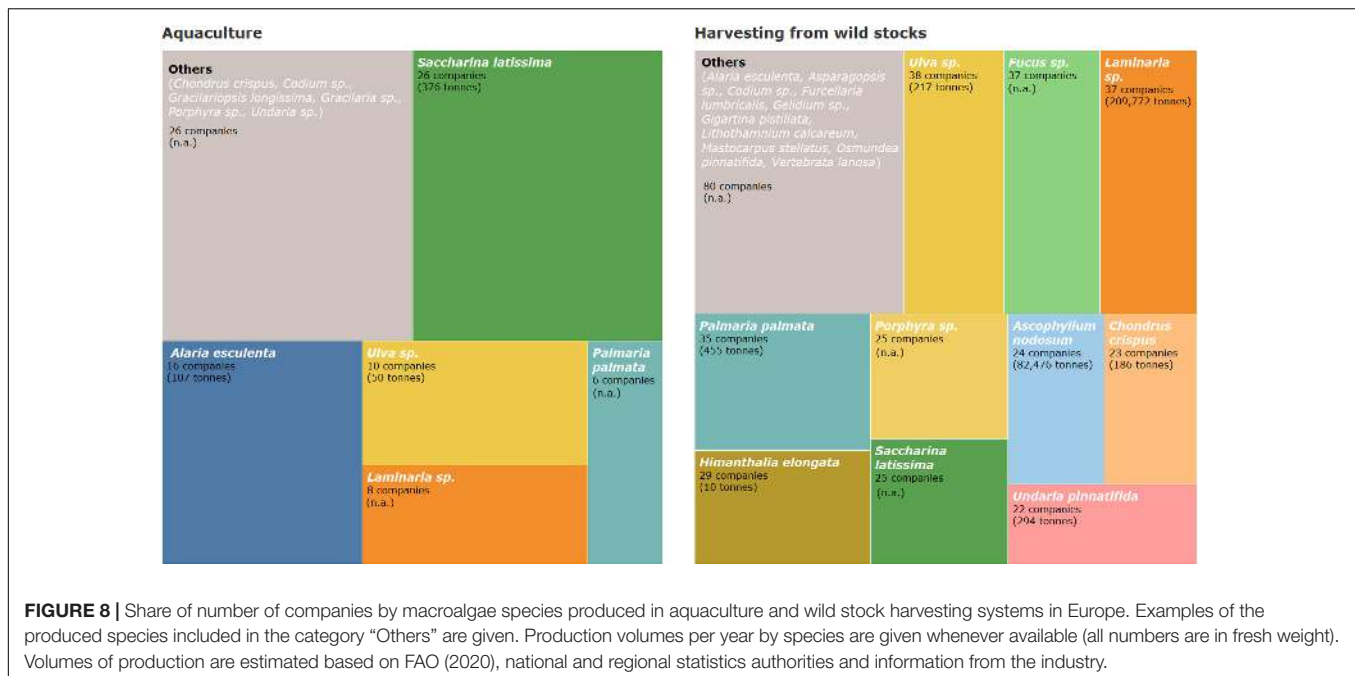
Peteiro et al., 2016) and rich nutritional content for human food and animal feed (Schiener et al., 2015, 2016). According to the number of seaweed producing companies by target species (Figure 8), *Alaria esculenta*, *Ulva* spp., *Laminaria* sp. (mainly *L. digitata*) and *P. palmata* are also important species in the European aquaculture sector. Yet, comprehensive data on volumes produced for certain seaweed species are not available (Figure 8). Other examples of cultivated species in European waters are *Asparagopsis* sp., *Codium* sp., *Gracilaria* sp., *Gracilariopsis longissima*, *Porphyra* spp., and *Undaria* sp.

In Norway, at sea licenses for cultivation of *P. palmata*, *Ulva* spp., *L. digitata* and *Porphyra* spp. have been issued but these units are still not operational (Stévant et al., 2017). In

Ireland there is a commercial demand from other industries for the cultivated biomass of *P. palmata* and *L. digitata* and there are currently 17 applications submitted to cultivate a variety of seaweed species including *A. esculenta*, *S. latissima*, *L. digitata*, *P. palmata*, *Porphyra* spp., and *M. stellatus* (Mac Monagail and Morrison, 2020).

(b) Harvesting From Wild Stocks

Harvesting from wild stocks targets a much wider variety of species in comparison to seaweed aquaculture and the volumes produced are also higher (Figure 8). The most collected seaweed in Europe in terms of volume is *Laminaria* spp. (including *L. hyperborea*, *L. digitata*, and a very small proportion of



L. ochroleuca), with more than 0.2 Mt of harvested biomass. *L. digitata* is the main exploited species in France where it is collected seasonally (Alban et al., 2011; Davoult et al., 2011), while *L. hyperborea* is the main species exploited in areas such as Norway where it is harvested all year-round (Frangoudes, 2011; Vea and Ask, 2011). *Laminaria hyperborea* and *L. digitata* are also harvested to a lower extent in Ireland (Mac Monagail and Morrison, 2020), and in Iceland, respectively. *Laminaria ochroleuca* is harvested in Spain (Galicia), where species such as *L. hyperborea* and *S. latissima* are no longer approved by the regional seaweed exploitation plans (García Tasende and Peteiro, 2015).

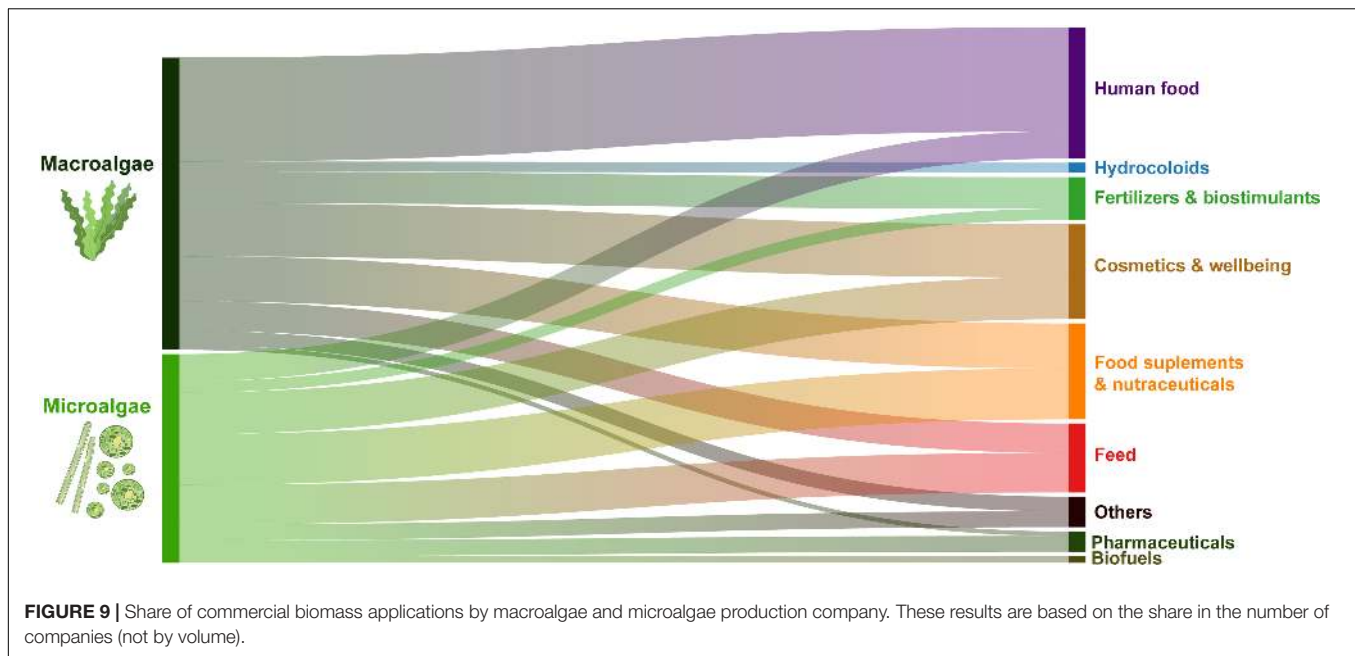
Ascophyllum nodosum is harvested in Europe at an annual rate of approximately 0.1 Mt (FW) per year (Figure 8), being one of the main species traditionally collected in countries like Ireland, Iceland, and Norway (Frangoudes, 2011; Mac Monagail and Morrison, 2020) and, to a lesser extent, in France.

A variety of other species are collected in different countries but contribute with much smaller biomass volumes (Figure 8). This is related to the commercial interest of the species as well as to the morphology and the commercial applications of the produced biomass. Species like *Porphyra* spp., *Ulva* spp. or *P. palmata* have much lower individual biomass than kelp species or fucoids like *Laminaria* spp., *A. nodosum* and *Fucus* spp. Additionally, as a result of the natural availability of stocks, species like *A. nodosum* or *Laminaria* spp. are primarily used for low-value, high volume applications like hydrocolloid extraction and fertilizers. Seaweed biomass used for food or the extraction of high added-value bioactive compounds is needed in much smaller quantities but represents a higher value per unit of biomass (Hafting et al., 2015). Another critical factor is that the production of some species is limited to particular geographic regions. This is the case of the harvesting

of agarophytes (*G. corneum* and *Pterocladia capillacea*) in the Iberian Peninsula (center-south of Portugal, Azores archipelago and the north of Spain) which accounted for approximately 5000 tons (FW) in 2018 (these values may be even higher given that data from some northern Spain regions are not available). This is also the case for the harvesting of *F. lumbricalis* in Estonia, which reached 60 tons (FW) in 2019 (Ilmjärvi personal communication).

Biomass Applications

Most of the seaweed companies in Europe direct their biomass production to food (36%), food-related uses (15%) i.e., food supplements, nutraceuticals and hydrocolloid production and, to feed (10%), accounting for 61% of the total uses (Figure 9). Cosmetics and well-being products also contribute to a significant share of the biomass uses (17%) while all other applications (e.g., fertilizers and biostimulants) contribute individually less than 11% of the total share (Figure 9). Commercial applications such as biofuels, bioremediation or biomaterials (listed under “Others”) or pharmaceuticals have only a small share at the European scale (Figure 9). These values refer to the number of companies directing the produced biomass to each of the uses which do not necessarily reflect the volumes allocated for each application. Besides, companies that are only involved in processing are not accounted for in this work; thus, the picture may be incomplete for some of the commercial uses. This is the case of the hydrocolloids sector using *Gelidium* sp., *Laminaria hyperborea* and *A. nodosum* as feedstock which requires high biomass volumes. Several of these hydrocolloid producing companies are among the largest in Europe exploiting a significant share of the harvested resources (Peteiro, 2018). It is to be noted that companies sourcing biomass from outside



Europe and purely transforming companies were excluded from this analysis.

Laminaria hyperborea biomass in Europe is mainly allocated to the production of extracts used for alginates, supplying 25% of the world alginates manufacturing (Frangoudes, 2011; Rebours et al., 2014; Stévant et al., 2017). The alginate industry also uses *A. nodosum* biomass, however, in countries like Ireland, the current production is mainly used as horticultural products (feeds, fertilizers, and biostimulants) (Guiry and Morrisson, 2013; Mac Monagail and Morrison, 2020). *G. corneum*, collected in Portugal and Spain, accounts for a large volume of the annual algae national production being among the top suppliers of the agar manufacturing industry (Callaway, 2015).

Food is the primary market in several companies for the seaweed biomass in Europe (Figure 9). The volumes produced are much smaller than the ones directed to hydrocolloid manufacturing but the prices per biomass unit are higher and there are many European companies specializing in selling seaweed products for the food market. Currently, several edible seaweed species are sold fresh or dried for direct consumption, used as condiments or incorporated in other formulations (e.g., dressings, sauces, canned seafood, bread, pasta, salt) in several European countries (Mouritsen et al., 2013; Le Bras et al., 2014, 2015; García Tasende and Peteiro, 2015). Some species like *L. digitata*, *C. crispus*, and *P. palmata* have an historical record of consumption as food (García Tasende and Rodríguez González, 2003; Mouritsen et al., 2013; Mac Monagail et al., 2017). *Himanthalia elongata*, harvested in Europe for centuries and used as fertilizer, food and for hydrocolloid extraction, is currently collected in France, Ireland and Spain mainly for human consumption (Stagnol et al., 2016). *Alaria esculenta* and *S. latissima* are often sold directly for human consumption or as high added-value food ingredients (Stévant et al., 2017).

Palmaria palmata is considered a food delicacy in Ireland with most of the produced biomass consumed internally since the demand is higher than the supply (Mac Monagail and Morrison, 2020). The historical consumption of this species is documented in France, Iceland, and Ireland and it is currently one of the most popular species used for human consumption in Europe (Mouritsen et al., 2013). *Fucus spiralis*, *Porphyra* spp., and *Osmundea pinnatifida* are consumed traditionally in the Azores archipelago (Patarra et al., 2011). In Spain, other kelp species such as *L. ochroleuca* and *U. pinnatifida* and the kelp-like species *Saccorhiza polyschides* have also been exploited for human food since the 1990s. More recently, other edible species are also used such as *Codium* spp., *Gigartina pistillata*, *Dilsea carnosa*, *O. pinnatifida* or *Nemalion helminthoides* (García Tasende and Rodríguez González, 2003; García Tasende and Peteiro, 2015). Yet, in some countries such as Norway, Greece, Estonia or Portugal (except for some islands of the Azores archipelago) seaweed consumption is marginal.

The retail price of seaweed biomass used for direct consumption varies with the product formulation (dry seaweeds have usually lower prices), species identity, production method (biomass from aquaculture generally entails higher production costs) and the amount of seaweed used. The market value is generally high, i.e., on average more than 100 € kg⁻¹ for dried and flaked seaweeds (Le Bras et al., 2015). In the current study the prices from online shops were consulted for a total of 12 dried seaweed species from 20 different companies spread by four countries. The average price was estimated at 107 € kg⁻¹ of dry seaweed. A closer outlook to the online algae market in Spain illustrates that the edible seaweeds with the highest market value (average value on dry weight) are *Porphyra* spp. (commercialized as nori) [251 € kg⁻¹ (ranging from 383 € kg⁻¹ for nori sheets and 179 € kg⁻¹ for nori flakes)], *Codium* spp. (155 € kg⁻¹), *Gracilaria*

sp. or *Gracilariopsis longissima* (155 € kg⁻¹), *P. palmata* (114 € kg⁻¹), *U. pinnatifida* (108 € kg⁻¹), *Laminaria* spp. or *S. latissima* (88 € kg⁻¹), *H. elongata* (86 € kg⁻¹), *C. crispus* (72 € kg⁻¹), and *Fucus* spp. (25 € kg⁻¹).

The nutritional properties of some seaweeds species make them an exciting feedstock as a source of food and food applications: the relatively high content in protein [generally higher in red and green algae (up to 44% of dry mass) than in brown algae (10–24% dry weight)] and dietary fibers (33–62% dry weight) (Holdt and Kraan, 2011; Patarra et al., 2011; Wells et al., 2016), the high-quality profiles of amino-acids (with glutamic and aspartic acids as the most abundant) (Holdt and Kraan, 2011; Maehre et al., 2014) and the high concentration of polysaccharides (e.g., laminarin, fucoidans, mannitol; 4–76% dry weight) and minerals (Cofrades et al., 2008; López-López et al., 2009; Holdt and Kraan, 2011). Seaweeds have a low lipid content (usually less than 5% dry weight) being the long chain polyunsaturated fatty acids (PUFA) and carotenoids the most relevant for nutrition (Holdt and Kraan, 2011). Seaweeds are increasingly used in the food supplements and nutraceuticals market and in cosmetics formulation. Bioactive compounds from brown algae (e.g., fucoidans, fucoxanthin, laminarin, polyphenols) and red algae (e.g., phycoerythrin) are used as colorants, antioxidants and recognized by their nutritional properties. Currently, research findings on the potential bioactive and functional properties of extracted seaweed compounds suggest positive effects on human health from its anti-bacterial, anti-fungal and anti-inflammatory activity (Holdt and Kraan, 2011; Hafting et al., 2015). However, the extraction of these high value-added substances involves specific technologies with associated high investment costs (Stévant et al., 2017). The quantification of the beneficial claims and digestibility and bioavailability pathways of the use of these products (for macro and microalgae) still needs further evidence support (Wells et al., 2016). Additionally, the role of seasonal, environmental and geographical variation in the nutritional properties of seaweeds needs to be better documented to support nutritional claims (Wells et al., 2016). Seaweed biomolecular composition can change markedly in response to seasonal variation in environmental factors such as salinity, nitrogen content and water temperature (Marinho-Soriano et al., 2006; Zhang and Thomsen, 2019).

Seaweed biomass has also been used in feed meals for marine and terrestrial organisms. Its positive role in reducing enteric methane emissions from cattle was in the spotlight as a result of recent studies (Maia et al., 2016; Roque et al., 2019; Kinley et al., 2020). Species such as *A. nodosum* are also extensively used as feed ingredients for livestock and pets (Frangoudes, 2011; Holdt and Kraan, 2011). *Saccharina latissima* has also been integrated as meal in animal feed (Stévant et al., 2017) and the use of kelp meals for abalone feed is common in some European countries (e.g., Ireland) (O'Mahoney et al., 2014). Currently, the cost and scale of producing seaweed-based protein for fish feed applications is not yet competitive with other protein sources with a high environmental footprint such as soy. The upscaling of the production and optimization of the processing methods is expected to place seaweed biomass in

a better market position for feed applications in the future (Emblemsvåg et al., 2020).

MICROALGAE and SPIRULINA spp.

Germany, France and Spain host the largest number of microalgae producers in Europe (Figure 2). The same countries (together with Italy) have the largest number of Spirulina producers but France dominates the production landscape with 65% of the mapped production units in Europe (Figure 2). Microalgae and Spirulina production is located mainly on inland sites (Figure 3). From the European countries included in this study, 16 have microalgae and 15 have Spirulina production plants (Figure 2).

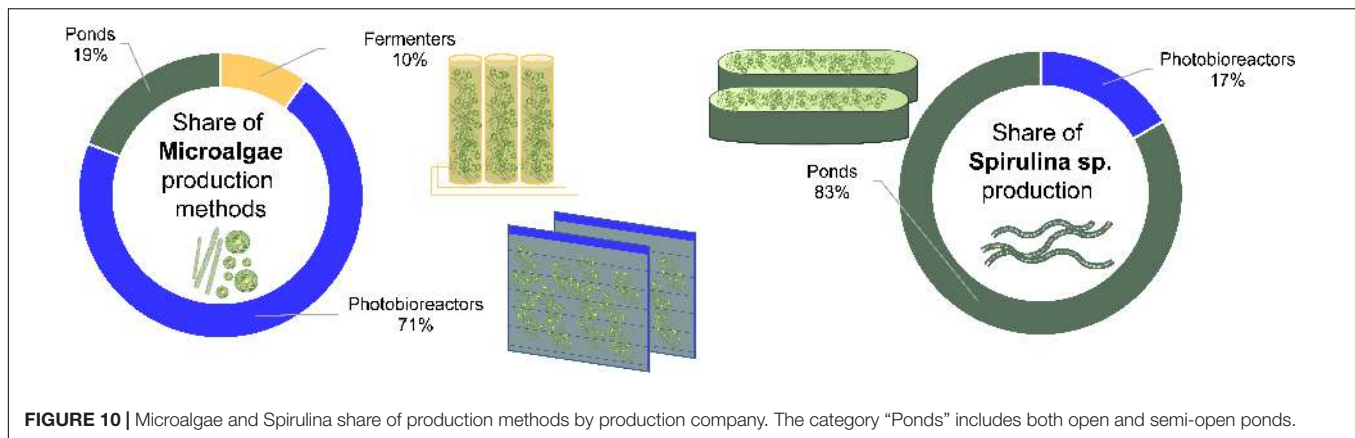
Production Methods

Microalgae are widely cultivated by different production methods and used in several commercial applications. Some production plants combine different production systems, e.g., photobioreactors (PBR) with fermenters or open ponds. Overall, PBR are the most common system used for microalgae production (71%), while open ponds and fermenters represent 19 and 10% of the total production units, respectively (Figure 10). For Spirulina the primary production method used is open ponds (83% of the companies) (Figure 10). All of the microalgae producing countries dominantly use PBR although some (e.g., Spain) also have a high share of production in open ponds (Figure 4). In eight out of the 16 countries producing microalgae, fermenters are also used for the biomass cultivation although the share of this method is relatively low (10%) (Figure 4).

Different cultivation methods have specific features that make them more adequate for the production of certain species and commercial applications. Factors like land requirements, construction and operational costs, technological development, maintenance and control of environmental parameters vary according to the cultivation method used (Zhu, 2015).

Photobioreactors, which is the most commonly used method of microalgae production in Europe (Figure 10), have associated high investment and operating costs as well as large energy requirements. However, within this technology significant differences are dependent on the type of PBR used. The closed PBR technology offers a variety of systems – from green wall to tubular PBR systems made of glass or plastic where the tubes are installed in horizontal or vertical arrays, each of the layouts having benefits and drawbacks in terms of cost and production stability. Closed PBR is the production method used for the production of high-value low-volume products for nutraceuticals, cosmetics, and pharmaceuticals. This technology allows for stricter control of the environmental factors and biomass quality and increases the photosynthetic efficiency and productivity of the production systems (Narala et al., 2016; Acien et al., 2017).

Cultivation in open ponds involves lower investment, operational and energy costs and has the potential to produce higher biomass volumes (Narala et al., 2016). This production method is thus more commonly used in the production of biomass for low-value applications, although some technical issues still need to be solved to unfold its potential in the



upscaling of algae biomass production for uses such as biofuel (Prussi et al., 2011; Narala et al., 2016; Acién et al., 2017). The disadvantages of open cultivation systems are the increased risk of contamination, lower control of the environmental conditions and greater land and water requirements (Murthy, 2011; Mayers et al., 2016; Costa et al., 2019). Additionally, most of the European countries have sub-optimal climate conditions for large-scale outdoor microalgae production (Vigani et al., 2015). In fact open ponds are the preferred method for Spirulina production in Europe (Figure 10). Actually, open ponds were the first microalgae industrial cultivation systems widely applied, and are used by 83% of the companies operating large-scale Spirulina cultivation plants. This species (together with *Chlorella* spp.) is the most commonly cultivated in open ponds worldwide (Mobin and Alam, 2017; Costa et al., 2019).

Hybrid systems combining open and closed cultivation methods are also used, allowing for a first cultivation step where contaminations and biomass traits are better controlled in photobioreactors with the subsequent transference of the inoculum to open ponds for increased biomass growth and lipid accumulation (Murthy, 2011).

Fermenters are currently used by a minority of the European microalgae producers (10%, Figure 10). They are a more recently developed method that allows for higher productivity and densities, control of contamination and manipulation of the biomass quality and profiles during the first growth phases of microalgae cultures (Barros et al., 2019). With this method microalgae cultures are grown heterotrophically using organic compounds such as sugars as carbon source. Production in fermenters can be combined with other methods such as autotrophic systems (photobioreactors or open ponds) since the highly concentrated inoculum obtained can be used to minimize the limitations (e.g., contamination, scalability) of these systems (Barros et al., 2019). Even if not as common as heterotrophically grown microalgae fermenters, it is also possible, although not as common, to grow algae autotrophically in fermenters by using artificial light or in mixotrophy (light and sugar). Fermentation technology has the potential for upscaling the production volumes while reducing production costs. The long-term sustainability of this production method needs to be better studied since the use of organic carbon substrates has

been argued to have a higher carbon footprint than autotrophic production (Murthy, 2011).

Microalgae production has proven environmental benefits but also potential adverse impacts related to the high water and energy demand, management of wastewater, emission control, land use and risk of microbial contamination (Usher et al., 2014; Mayers et al., 2016; Béchet et al., 2017). More empirical evidence is needed to compare the environmental footprint of this production method with other feedstocks for commodities such as land-based cultures.

Phototrophic production of microalgae in any kind of pond system or photobioreactor is facing the main challenges of light limitation and a missing scalability of reactors. Hence, there is a need of technological and material innovation, a need for adapted strains as well as a rethinking about the use of waste streams (e.g., special waste waters, CO₂ emissions, heat) and its impact on production costs. A global mapping of the main productions costs (energy, labor costs, water/waste water) together with climate data could help to estimate the economic efficiency of an algae farm according to the technology, scale and algae strain on a certain location. As microalgae are always produced in containment, nutrition monitoring is more feasible, but it is still in its infancy. More advanced in-line measurement and dosing devices for monitoring and adjusting the concentrations of single elements in the culture media would greatly enhance productivity as depletion of even one single component strongly decreases biomass production or reduces compound contents. Similarly, nutrition monitoring would also help to reduce production cost as well as the environmental load caused by the amount of nutrition-loaded waste water (Jaywant and Arif, 2019).

Species Produced

Only a minor share of the naturally occurring microalgae species are exploited commercially. In Europe it has been argued that the rate of exploitation of new species is also hindered by administrative burdens, namely the need for any novel species to go through the Novel Food regulation (EU, 2015) before it can be placed on the food market. The stakeholders from the algae industry claim that these procedures represent an expensive and time-consuming endeavor (Araújo et al., 2019b). Some of these

species are already extensively cultivated at the industrial scale and have a well-established market (Carrasco et al., 2018).

The market value for these species at the moment is very much based on their potential as a source of high-value bioactive and functional compounds such as pigments (e.g., carotenoids such as β -carotene and fucoxanthin), anti-oxidants (e.g., astaxanthin, fucoxanthin), long-chain polyunsaturated omega-3 fatty-acids [e.g., docosahexaenoic acid (DHA), eicosapentaenoic acid (EPA)], phycobiliproteins (phycocyanin) and polysaccharides (Marcati et al., 2014; Sun et al., 2014; Mobin and Alam, 2017).

According to the results of this study, the most cultivated microalgae species in Europe in terms of the number of companies are *Chlorella* spp., *Nannochloropsis* spp., and *Haematococcus pluvialis* (Figure 11) together with *Spirulina*. These species are also reported among the most widely exploited species worldwide over the last decades for biotechnology applications (Mobin and Alam, 2017). Indeed, *Chlorella* and *Spirulina* are the most produced species in terms of dried algae volumes (Vigani et al., 2015). Other species such as *Tetraselmis* sp., *Tisochrysis lutea* (formerly *Isochrysis galbana*), *Dunaliella salina*, *Phaeodactylum tricornutum*, *Porphyridium* sp., and *Scenedesmus* sp. are also among the top produced species in Europe (7 or more companies) (Figure 11). Some other species such as *Thalassiosira* sp., *Acutodesmus obliquus*, and *Chaetoceros muelleri* show less interest from an industrial point of view (in terms of the number of companies) but they are still produced in Europe (Figure 11).

Official statistics on microalgae production volumes are almost non-existent at the European scale and the data available from FAO or Eurostat are limited and fragmented. In this study several data were gathered on the production volumes at the European scale showing an approximate production of 182 tons dry weight (DW) of microalgae and 142 tons (DW) of *Spirulina*. *Chlorella* spp. and *H. pluvialis* are the most produced microalgae in terms of volumes, corresponding to more than 80% of the total values gathered in this study (Figure 11). This information on produced volumes needs to be taken with caution because data reported refer in many cases to estimates of production values and some countries and companies producing microalgae biomass were not included in this sum.

Biomass Applications

Microalgae species are sources of different bioactive compounds and thus used in a variety of commercial applications.

Chlorella spp. was the first species to be cultivated on an industrial scale in the 1960s in Japan. According to our study, this species is produced in 11 European countries. This species has a high protein (up to 60%) and carbohydrates content and it is also rich in B vitamins (Costa et al., 2019). *Nannochloropsis* sp. is an important source of EPA (Mobin and Alam, 2017). *Haematococcus pluvialis* has the capacity, under stressful conditions, to accumulate high quantities of astaxanthin a high-value antioxidant carotenoid. Indeed, *H. pluvialis* is the leading natural source of commercial astaxanthin (Mobin and Alam, 2017) which is currently the most produced carotenoid (Borowitzka, 2013). *Spirulina* is very rich in proteins and antioxidant compounds. It is used for the extraction of pigments

such as phycocyanin, a blue photosynthetic pigment which is used in health, cosmetics and food applications (Mobin and Alam, 2017). *Dunaliella salina* is an excellent natural source of the antioxidant β -carotene (Borowitzka, 1999; Mobin and Alam, 2017; Costa et al., 2019). *Porphyridium* sp. is used for the extraction of exopolysaccharides and pigments (phycoerythrin).

Food supplements and nutraceuticals (24%), cosmetics (24%), and feed (19%) are the main applications of microalgae biomass, contributing together to 67% of the total uses (Figure 9).

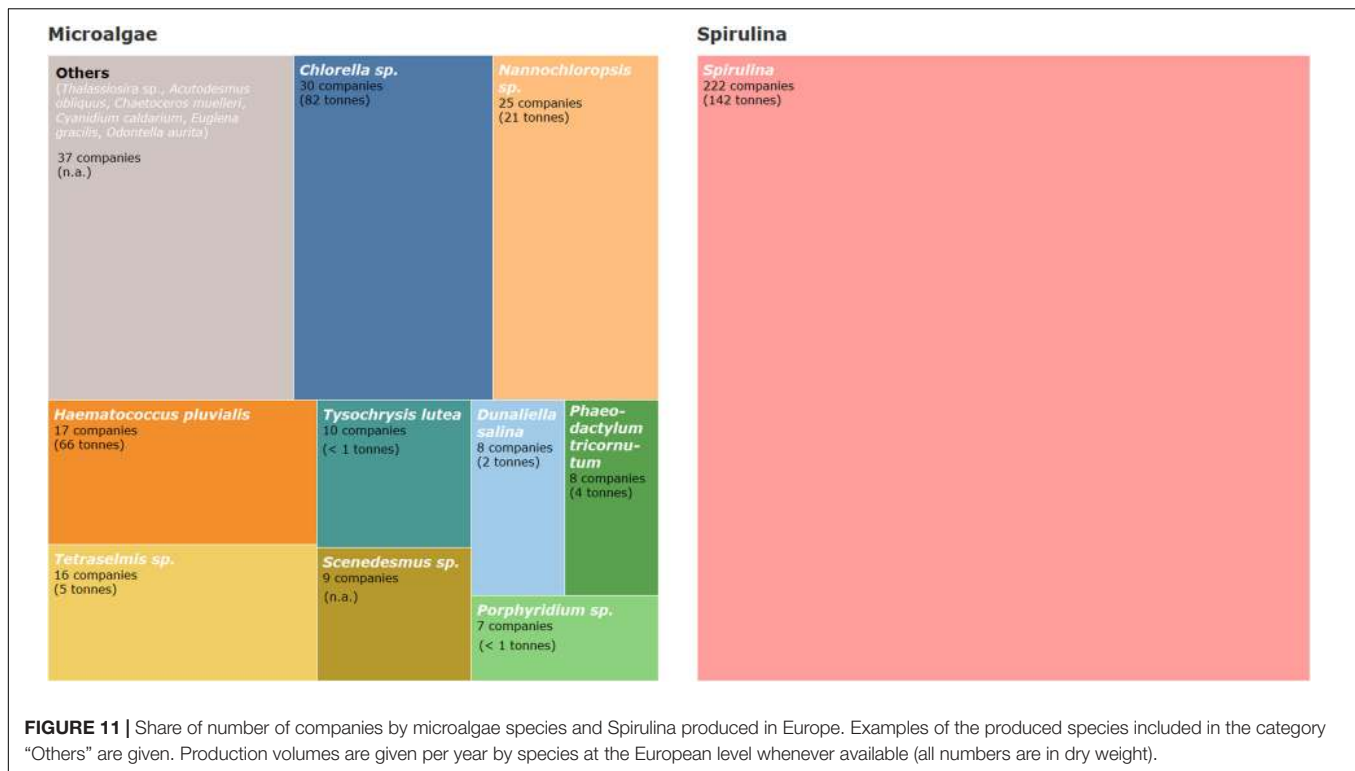
Spirulina production is mainly directed to food and food supplements and nutraceuticals, contributing to 75% of the reported uses (data not shown).

Although industrial microalgae production was already established a long time ago the high production costs and technological constraints as well as gaps in the scientific understanding of large scale algae cultivation, limit the commercialization of the biomass as high-value products excluding large scale low-cost applications such as fuel (Caporgno and Mathys, 2018; Kiesenhofer and Fluch, 2018; Barros et al., 2019).

Microalgae biomass from species such as *Chlorella* spp. and *Spirulina* has historically been used in the food industry as dietary supplements providing vitamins, highly digestive proteins, polysaccharides and lipids (e.g., PUFA) (Stanic-Vucinic et al., 2018). It is estimated that these 2 groups have up to 70% of protein content (Wells et al., 2016; Niccolai et al., 2019) and a well-balanced amino acid profile (Becker, 2007). *Spirulina* is also regarded as a good source of vitamins, macro- and micro-elements essential fatty acids (Stanic-Vucinic et al., 2018). The use of microalgae as a sustainable alternative to animal-based food to fulfill the proteins demand of the growing global population has been discussed in recent studies (Caporgno and Mathys, 2018). These and other species such as *Dunaliella* sp. and *H. pluvialis* can be used as a source of nutrients and high-value extracts by adding them to food products and feed and increase their nutritional value. They can also be used as natural colorants in a variety of food products (e.g., bread, pasta, cookies, ice cream, candy, and beverages).

Some species (e.g., *Chlorella* spp., *Spirulina*, *Dunaliella* sp., *H. pluvialis*) produce compounds associated with potentially beneficial health bio-activity, for example anti-fungal, anti-viral, anti-carcinogenic, anti-inflammatory, anti-oxidant, and immune system stimulant. Thus, they are used in a variety of health products, including tablets and capsules. Additionally, some species contain a high content of dietary fibers which have positive health benefits (Niccolai et al., 2019). However, further scientific evidence is needed to understand the health-related benefits of microalgae extracts and the bioavailability of the bioactive compounds (Caporgno and Mathys, 2018).

Chlorella spp., *Nannochloropsis* sp., and *T. lutea* are among the microalgae species used as feed in aquaculture and animal farming. In the aquaculture industry microalgae have been regarded as a sustainable alternative source to omega-3 from fish oils while the market for microalgae biomass as animal feed is already of considerable size (Carrasco et al., 2018). However, microalgae cannot yet be regarded as an alternative to vegetables or cereals as protein source for the



feed market (Vigani et al., 2015). Microalgae are an important source of EPA and DHA (products with high commercial value) and can be directly incorporated in formulations for larvae and juvenile feed (mainly for rotifers that are then used for breeding crustaceans and fish). Astaxanthin from *H. pluvialis* was used as coloring pigment in aquaculture and the antioxidant activities have positive health effects and enhance the immunological system.

The market value for microalgae biomass varies depending on several factors such as the production system, production costs (energy and work force), geographical origin, certification schemes (e.g., organic production) and step of the value chain [e.g., Business to Business (B2B) or Business to Consumers (B2C)]. Based on consultation with algae producers, B2B values (on dry weight) for *Chlorella* sp. and Spirulina (the 2 main species marketed for food and food supplements), vary between 25–50 € kg⁻¹ and 30–70 € kg⁻¹, respectively. In contrast, B2C values for both species range between 150 and 280 € kg⁻¹ (higher values for small package sizes, finished products). For *Nannochloropsis* sp., the most relevant species for feed, B2B price values are in the range of 30–110 € kg⁻¹ and B2C market value (as marine phytoplankton) can go up to 1000€ kg⁻¹. Speciality algae as well as algae used for the extraction of high value products are in a different price range. For example *H. pluvialis* B2C price varies between 150 and 300 € kg⁻¹ while B2B price for astaxanthin oleoresin, based in pure astaxanthin, is in the range of 6.000–8.000 € kg⁻¹. The emerging applications of microalgae biomass face an increasing market demand and have still room for a strong increase in the production volumes.

The extracts of some microalgae species (e.g., *Nannochloropsis* sp., *Chlorella* spp., Spirulina, *Dunaliella* sp., *Schizochytrium* sp., *Tetraselmis* sp., *Porphyridium* sp., *P. tricoratum*, and *H. pluvialis*) have been used in the cosmetic industry for skin regeneration, moisturizing, anti-aging, and protection from UV radiation (Ariede et al., 2017).

The use of microalgae as a feedstock for biofuel (biogas, biodiesel, and hydrogen) production has been the focus of several research and industrial efforts over the last decades. Microalgae have been identified as a promising feedstock for biofuel production since they do not compete for arable land with food and feed crops. They also show a high lipid content producing high oil yields. However, further technological developments are needed to upscale the production volumes and reduce the production costs that can turn the biofuel production from microalgae biomass a reality in the near future (Zhang et al., 2014).

Over the past decade the algal biorefineries have been investigated as an approach to optimize the use of multiple components of the feedstock for different applications. In addition, if connected to other industrial infrastructures, the algae production plants can benefit from the associated resources (e.g., water, heat) and function as a source of additional services such as wastewater treatment (Mayers et al., 2016). This synergy is expected to reduce the costs and increase the environmental sustainability of microalgae production but further research is needed on the optimization of such approach (Béchet et al., 2017).

CONCLUSION AND FUTURE DIRECTIONS

This study illustrates the European algae industry as a bio-based sector with a considerable potential to further develop and contribute to critical societal challenges such as the EU carbon neutrality, an innovative food system that ensures access to nutritious and sustainable food, and, ultimately, the support to a sustainable and circular European bioeconomy. This potential is illustrated by the number of algae biomass production units mapped, spread across 23 European countries and covering different environments and production methods. Although many of the compiled production units are of small size, the activities related to the sector represent an important source of livelihood in several coastal areas in Europe. The production of seaweed is still very dependent on the harvesting of wild stocks, but the growing trend in seaweed aquaculture demonstrated by the number of operating companies mapped, represents new opportunities for the multiuse of the maritime space and the sustainable production of algae biomass while providing a series of ecosystem services such as bioremediation and carbon uptake. In contrast, the main production method of microalgae is photobioreactors which illustrates the potential of the European microalgae biomass in the market of high value products but also the non-readiness of this production system to support large scale biofuel production from algae biomass. In terms of the number of production units, the sector is well balanced between *Spirulina* (49.7%) and algae production (50.3%). For the latter, the microalgae production units are still a minority (33%). Further, the algae sector in Europe currently relies on the production of large biomass volumes of a reduced number of species. The results of this study also show that a variety of other species is currently produced which can be an opportunity to upscale the production volumes and meet increasing market demands or explore other high-value commercial applications based on low biomass volumes. Although currently the algae production in Europe is mainly directed to food and food-related uses, this study shows a variety of other applications being progressively established in the market. In contrast, less commercially important species are being researched, showing the innovative and wide range of influence and possibilities for the sector.

In Europe the algae and *Spirulina* sector is still immature and thus relatively small. Its future growth relies on technical innovations to upscale the production, while reducing the production costs. Additional key needs are to expand and diversify the market for algae and *Spirulina* commodities and to develop uniform standards for existing products and production methods while informing customers and simplifying regulatory and administrative procedures (e.g., for novel algae-based products, licensing of production units).

The biorefinery approach (algae biofactory) is currently being investigated as a mean to increase the environmental sustainability and economic feasibility of existing conventional industrial processes. Different potential conversion pathways are being researched for the use, extraction and valorization

of algae biomass biorefinery products (Zhang and Thomsen, 2019). Additionally, technological improvements in the biomass cultivation systems are intensively researched (e.g., offshore aquaculture, biomass optimization practices, technology readiness for microalgae production and processing, incorporation of algae production in wastewater treatment and CO₂ mitigation).

Yet, the expected boost in the development of the algae and *Spirulina* sector in Europe in the coming years needs also to be coupled with the protection of the environmental and recreational services provided by these coastal and fresh water-based ecosystems in order to guaranty the establishment of sustainable and responsible industries.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because part of the data are confidential. Requests to access the datasets should be directed to RA, rita.araujo@ec.europa.eu.

AUTHOR CONTRIBUTIONS

RA: conceptualization, methodology, investigation, writing-original draft, project administration, and supervision. FV: investigation, data curation, validation, writing-review and editing. JS: data visualization, data curation, writing-review and editing. IA, AB, SF, MG, TI, ML, MM, SM, CR, TS, and JU: investigation, writing-review and editing. FG: investigation, data curation, writing-review and editing. CP: investigation, data visualization, writing-review and editing. All authors contributed to the article and approved the submitted version.

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The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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