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Renewable Energy 165 (2021) 842–862

Contents lists available at ScienceDirect

Renewable Energy

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

Microalgae in a global world: New solutions for old problems?

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ARTICLE INFO

Article history:
Received 6 July 2020
Received in revised form
22 October 2020
Accepted 5 November 2020
Available online 9 November 2020

Keywords:
Pollution control
Resource recovery
Bioresource
Bioenergy
Biofuel
Biorefineries

ABSTRACT

The human population blast has brought several problems related with the overconsumption of a wide range of feedstocks and natural resources conducting to their risk of depletion. The consumption of fossil fuels is an example, with increasing levels of exploitation and negative impacts caused by their use. Anthropogenic activities have triggered the over accumulation of many hazardous substances and wastes which are regarded to be detrimental to life in the Earth and to the various planet ecosystems. There is an urgent need to restore natural resources and unwanted residues and wastes to levels prior the demographic explosion. Microalgal biotechnology appears to be pivotal to achieve this goal in a near future to come. This review presents the current resource problems affecting the Earth and how microalgae are expected to be an important part of the solution, discussing how the production of renewable energy from microalgae can help in an integrated way to mitigate different environmental problems. Microalgae are able to convert wastewaters, CO_2 and organic residues in marketable biomass for different uses, including biofuels, converting waste in value. An inventory of current microalgal-based biorefineries in operation as well as a directory of companies, products and applications are also presented.

1. Introduction

The first step in solving a problem is to recognize its existence. Currently, serious environmental problems, such as water scarcity and climate change, which can trigger serious social problems on a global scale, are related to the exponential growth of population, urbanization intensive, use disordered land and fossil fuels. In this context, the United Nations launched the 2030 Agenda, establishing 17 sustainable development goals (SDGs), setting objectives in different sectors of society, with the aim of guiding actions towards improving people's living conditions [1].

SDG addresses 7 issues related to affordable and clean energy. The use of fossil fuels such as oil, coal and natural gas, emits approximately 6 billion t of carbon dioxide (CO_2) into the atmosphere [2]. In 2018, the energy consumed worldwide was in the order of 14,279,569 ktoe, of which approximately 14% came from renewable sources, such as hydropower, solar, wind, biofuels and waste [3]. Despite the advancement of renewable energy alternatives in recent years, their use is limited in view of the potential that presents [4] and mainly, in view of the urgent need for a paradigm shift in the sector.

In this context, the use of microalgae for the production of 3rd generation biofuels is gaining more and more attention. Algal biomass can be used to produce different biofuels, such as biodiesel, biogas, bioethanol and bio-oil, overcoming some of the main difficulties of 1st and 2nd generation biofuels [5]. The energy content of biofuels obtained from microalgae can reach values of the order of 35,800 kJ kg^{-1} for crude oil [6], 38,100 kJ kg^{-1} for bio-oil [7] and 39,900 kJ m^{-3} for biogas [8]. Microalgae have a high photosynthetic rate compared to higher plants [6], which means high biomass productivity. In addition, they can develop in areas unsuitable for agriculture [9], avoiding conflict related to food security and can be

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https://doi.org/10.1016/j.renene.2020.11.014
0960-1481/

produced during the wastewater treatment [10–12], considered as a nutrient recycling, without requiring potable water for its cultivation.

In a society that increasingly seeks specific solutions to specific problems, acting on environmental issues is a significant challenge. Therefore, this review aims to discuss how the production of renewable energy from microalgae can help to mitigate in an integrated way, different environmental problems.

This review follows an innovative systemic approach. This introduction (section 1.1) highlights the recent problems affecting the Earth which are being detrimental to life in every way, thus affecting the mankind. Later, new broadly recognized solutions will be listed in order to overcome previous listed problems (sections 2.1. and 2.2). Furthermore, the text goes deeper in detail, concerning the uses of microalgae in the fight of the abovementioned problems (sections 2.3 and 3), highlighting the technological flexibility of microalgae to solve problems locally (chapter 4). The performance of microalgae will be carefully presented, with quantitative indicators related to carbon (GHG) biofixation (section 2.3.1), wastewater treatment (2.3.2) as practical and proven tools for resource recovery in the frame of a new green-bioeconomy. Chapter 3 covers extensively bio-based products and biofuels from microalgae, highlighting pathways, processes and yields (productivities), acting as crucial data for the further development of microalgal-based biorefineries, regardless the type. Later on, a worldwide survey of already existing microalgae-based biorefineries of different technological readiness levels and size will be carried out on chapter 5 (for the very first time as authors know). Finally, on chapter 6, a list of worldwide current microalgal producers already established in the market will be presented, giving more emphasis to the commercial impact of microalgae in a global world. The main purpose of chapter 6 is to demonstrate that the microalgal exploitation is a current reality worldwide and a wide array of biobased products from this feedstock can replace fossil-based products already in the market with either environmental or sustainability advantage.

1.1. Old and recurring problems

1.1.1. Water scarcity

Water scarcity has been a determinant factor in several parts of the world, being required an efficient management of water resources. In addition to the uneven geographical distribution of water resources, climate change is increasingly imposing severe seasonal restrictions on places that did not have this concern. Scientific evidence confirms that the climate on the planet is changing, thus affecting societies and the environment [13]. These change generates extreme climatic events associated with intense population growth and affects the water availability and quality for basic human needs [14].

Consequently, water resources became a concern across the globe. Moreover, economic development, changes in consumption patterns, intensification of demand for inputs, agricultural and energy products generate an increase in demand for water resources [15], making their availability increasingly uncertain in the near future [13,14]. Approximately 2 billion people live in countries with some degree of water stress and about 4 billion people experience severe water scarcity during at least one month of the year. The water demand is expected to increase between 20% and 30% by 2050 compared to current levels [16].

Water is the primordial resource for agricultural and industrial services. While only 2.7% of the worldwide water is available as freshwater, only 30% of this water can be consumed for meeting human needs [17,18]. With the meteorological/hydrological changes, associated with increased water pollution, there is an urgent need for adaptation in water management worldwide [19,20].

1.1.2. Overpopulation and resource scarcity

It is evident that the increase in population has been causing greater demand for resources, not only for water, but also for food, services and energy, intensifying the biosphere degradation [21]. According to the United Nations, it is expected that in the next 30 years the world population will grow by up to 2 billion, reaching 9.7 billion inhabitants in 2050 [16]. The cities with higher population densities consume between 60% and 80% of all global energy and, as a consequence, generate about 75% of all CO_2 emitted in the globe [22]. Based on a non-organized growth model, many cities suffer due to the high consumption of energy and water, generating a large quantity of pollution [23], caused by demand from its technological infrastructures.

Since the industrial revolution, the world population has been intensively exploring non-renewable resources, affecting the ecosystems with the objective to supplier their needs. As a consequence, ecosystems have been disturbed or even destroyed at an accelerated pace, making impossible it's natural restoration [24].

De Bhowmick et al. [25] described that with the rapid depletion of fossil fuel resources it is unlikely that there will be an oil reserve after 2050 and adds that emissions from this energy source will cause irreparable environmental damage. In this scenario, the world faces the increasing scarcity of conventional energy resources, which would result in a race to adapt to the new world scenario and search for new means for the production of clean energy [26]. According to Trevors [27], humanity is addicted to oil extracted from hydrocarbons, one of the main sources of greenhouse gas emissions (GHG), which are also potential contaminants of soils and oceans. According to the author, it is important to realize an energy conservation program with the objective of the gradual replacement of fossil fuels with other less-polluting energy sources such as the use of biomass for the production of several biofuels such as biodiesel, bio-oil, bioethanol and biogas/biomethane, including the adoption of huge energy efficiency practices.

1.1.3. Overcontamination (soil, water and GHG)

With economic development, today's society consumed many more goods and products, increasing the production of solid wastes and wastewaters [28,29]. High GHG emissions are also a growing problem.

It's estimated that the amount of urban solid wastes generated worldwide is approximately 2.01 billion t per year. The forecast is this amount will exceed 3.40 billion t per year, by 2050 [30]. With these values, it is expected the incorrect deposition of contaminated residues in the soil as well as underground aquifers and surface waters. The main contaminants are usually heavy metals, besides nitrates, phenolic compounds, hydrocarbons, among others [31]. Many agricultural products accumulate these elements and can cause severe damage to human and animal health since ingestion is one of the main contamination routes.

Regarding wastewater, a report issued by UNESCO [32] recorded that only 8% of domestic and industrial wastewater is treated in countries with low-income. In high-income countries, the average percentage is 70%. The release of untreated wastewater can deplete dissolved oxygen in watercourses, leading to the death of the aquatic ecosystem. The nutrients contained in wastewater intensify eutrophication, another serious environmental problem that exists since the middle of the 20th century [33].

Forest deforestation and the production and consumption of food, as well as the production of fuels, wood, manufactured goods, roads, buildings, transportation, power generation, among others, are human activities responsible for GHGs emissions. Many times, the data are expressed in terms of the amount of CO_2, or its equivalent of other GHGs, emitted to the atmosphere [34]. Fig. 1 shows approximate percentage values of CO_2 emissions by the main countries.

Mahmud et al. [35] evaluated the CO_2 emission through different power generation plants. When comparing the emission of gas in power generation systems by hydroelectric plants versus biomass, values of 1,020 and 42.8 CO_2eq kWh^{-1} were obtained, respectively. In other words, using biomass to generate electricity, CO_2 emissions are 24 times lower when compared with the hydroelectric power plants. The production of energy from hydroelectric plants, despite being a source of "clean energy" generate GHG into the atmosphere due to the fact that the reservoirs built emit gases such as CO_2, methane (CH_4) and oxide nitrous (N_2O) [36]. Thus, the use of biomass is more advantageous for clean energy generation, since avoids dam construction where the waters become rich in nutrients increasing aquatic primary production, which causes water eutrophication and high GHG emissions [36,37]. In this scenario, occur an increase in the global demand for energy, allied to the use of non-renewable energy sources. For these reasons, exists the need to seek alternative sources that are less polluting and other solutions to reduce environmental damage [38].

2. New solutions

2.1. Water recycling

One possibility for the water resources management is to diversify supply alternatives through unconventional water sources. In this context, the use of treated effluents as a potential source of water supply for several activities stands out, with the additional benefit of reducing the negative impacts of their discharge into the environment [39]. Treated domestic sewage can represent an important source for activities that do not require drinking water, increasing supply security and reducing the energy consumption and other inputs in water treatment systems. Domestic sewage can supply water regardless of the time of year, unlike other possible sources, such as rainwater [40].

The water reuse has potential applications in many activities: in agriculture (irrigation of cultivated areas); in industries (reintroduction in the production process); in refilling underground aquifers; and in urban uses (fire prevention, street cleaning and landscape harmony) [41–44]. Many studies have been developed in order to expand the water reuse in the industrial scope. Aquim et al. [42] evaluated the use of the effluent from the leather industry after treatment by flotation and sieving. The treatment promoted the reduction of oils, greases and also chromium. Authors stated that with the water reuse, it is possible to save up to 36,000 L per day and reduce the consumption of chemicals in the process by up to 10 times. Buscio et al. [45] studied the water reuse in the textile industry using a treatment consisted of an electrochemical system assisted by UV radiation. Colour removal varied from 64% to 99%, meeting the production requirements and allowing 70% a reduction in water consumption. Tiwari et al. [46] evaluated the optimization of a wastewater treatment plant of the largest dairy industry in India, in order to improve the water reuse process. The authors stated that the implementation of the improvement measures could allow the reuse of 100% of the effluent. In addition, the plant may have a positive energy balance, through the production of biogas and a reduction in the energy consumption of aerators.

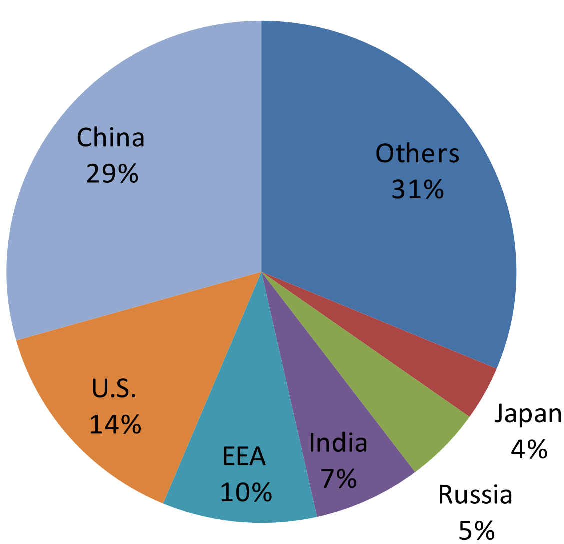

Fig. 1. Global CO_2 emissions by countries. Adapted from Ref. [34].

As mentioned, agriculture represents one of the main activities for water reuse, since it is responsible for around 70% of water demand worldwide [47]. This high consumption causes water scarcity to generate concerns related to food security, nutrition and livelihoods of various populations, in addition to socioeconomic aspects, due to the jobs generated in the sector [43]. The use of treated domestic sewage for agriculture can represent a source of greater confidence in water supply, as well as improving the efficiency of the use of this resource. These practice has been adopted in several countries, i.e. Tunisia, where the use of treated sewage for agriculture involves 20% of the produced effluents, which allows allocating of freshwater for drinking uses and minimizes the release of effluent into the water bodies [48]. In Israel, in 2010, 38% of agricultural demand was supplied by this source, being estimated 62% by 2050 [49]. This means a target that foresees an increase in the use of treated sewage in agriculture from 400 million m^3 to 900 million m^3 per year. The European Union is concerned about water scarcity on the continent and recently approved new rules to promote the reuse of water in agriculture, an activity that consumes 51% of the water on the continent [50]. The proposal will allow an increase in water reuse from 1.7 billion m^3 per year to 6.6 billion m^3 per year [50]. In Australia, it is estimated that in 2015–2016, 137,000 ML of the water consumed in agriculture came from the reuse from sources outside the farms [51]. However, this volume represents only 1.4% of the total consumed in agriculture in this country. The main ones supply sources are surface water and groundwater.

Despite the evident advantages of water reuse, there are limitations related to the treatment of effluents such as the health risks and public acceptance. In order for the benefits of water reuse to be fully enjoyed, it is necessary that the practice be critically accepted, considering the risks involved and the challenges presented in the definition of regulations for each specific activity. However, it is also required that the evaluation be carried out in a broader and holistic approach, in the context of circular economy of water management [52].

2.2. Resource recovery (a new green-bioeconomy)

From the context of the circular and green economy, resource recovery is an interesting option to obtain value from a waste [53]. Resource recovery can represent the new concept of green bioeconomy, englobing visions of circular, finite, renewable and sustainable resources (Fig. 2). Besides this, another relevant factor is

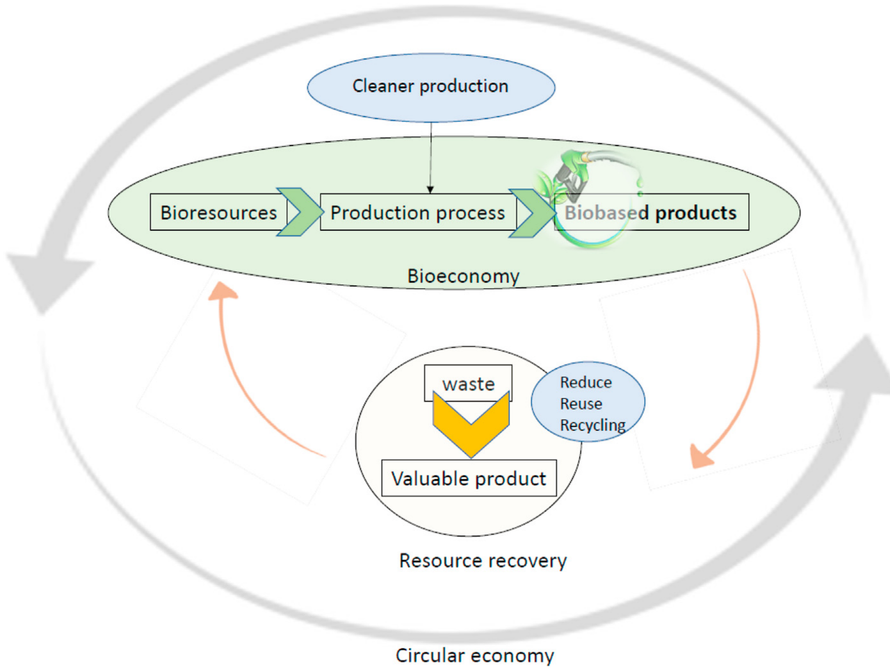

Fig. 2. Resource recovery in a circular and green bioeconomy context.

the negative environmental impact of the various resource production chain. For instance, in the industry of fertilizer the total energy consumption for the production of potash, phosphate and ammonia fertilizers is 13,800 kJ kg^{-1}, 17,500 kJ kg^{-1} and 78,239 kJ kg^{-1} respectively [54]. The Haber Bosch process for ammonia production is responsible for 1–2% of global energy consumption and 1.44% of global CO_2 emissions [55]. Regarding phosphorus, it is estimated that apatite, its finite source to be depleted in 50–100 years [56] or in 100–400 years, if technical advancements and the exploitation of new rocks are considered [57]. Oil is another example of finite resource, utilized as a feedstock for the production of different products. The world's oil consumption in 2018 was 99.8 million barrels per day, representing 1.5% of growth rate per annum [58]. Conventional power stations, based in oil, coal or natural gas, are responsible for emitting 344–941 kg CO_2 MWh^{-1} at capacities of 400–1200 MW [59].

Some industrial sectors have successful resource recovery examples, such as the traditional petrochemical industry and the dairy process industry. In the petrochemical industry, the recovery of waste heat has been applied for many years [60,61]. On the other hand, the resource recovery in the dairy industry is a more recent subject. The high valuable product whey protein powder is produced through a membrane module used to separate different portions of the milk waste [53].

Wastewater can be considered a problem that may cause several negative impacts in the environment, if not properly treated (as seen in Section 1.3). However, wastewater can also be considered as a resource. The energy content of wastewater is estimated to be 6.3 kJ L^{-1}, related to the chemical oxygen demand [62]. Wastewater sludge accumulates 98% of the ingested phosphorus [63] and approximately 20% of global phosphorus demand can be satisfied by recovering 3 million metric t per year of this nutrient from human waste [64]. Therefore, wastewater represents a resource to be recovered, rich in energy and very important from a circular economy perspective.

In the USA, the wastewater treatment plants (WWTPs) are responsible for 3% of national electricity consumption [65]. Secondary and tertiary treatments are energy-intense, ranging from 0.3 to 2.1 and 0.4–3.8 kWh m^{-3}, respectively, in developed countries [66]. The major negative impact of a conventional WWTP operation is the emissions of GHG [67–69]. According to the USA Environmental Protection Agency (EPA), in 2017, 14.2 and 5.0 MMT CO_2eq of CH_4 and N_2O, respectively, were emitted during the sludge digestion in this sector [70]. As the demand and costs for energy and water keep increasing, the vision toward wastewater treatment is changing. The linear "end of pipe" approach of WWTPs no longer meets the sustainability requirements of current society and municipal wastewater is being considered as a valuable resource, creating the water resource recovery facilities (WRRFs) [53], instead of aligned with the circular economy green.

In this context, advantages such as reduction of feedstock depletion and GHG emissions can be achieved, through resource recovery from the effluent, producing energy and reducing energy needs [53]. Besides sustainability appeal, the economic point of view is also an advantage of this approach because it allows adding economic value to waste, making the process economically attractive, in addition to being environmentally necessary. Waste from WWTPs contains nutrients, such as nitrogen and phosphorus, that can be recovered and used as fertilizers [71]. On the organic matter can also be obtained energy and heat through biochemical, thermal and chemical conversion processes. In addition, it is possible to get different types of biopolymers [72], metals [73] and cellulose [74] from the wastewater.

2.3. Microalgae fighting the overcontamination

2.3.1. Microalgae for GHG fixation

Microalgae have been studied as feedstock for different purposes, such as bioenergy production [75–77], soil conditioner and biofertilizer [78], and the source of protein for food and feed production [79,80]. These varieties of products can be obtained due to microalgae's ability to produce different compounds from their metabolism, allowing to meet the many demands of current society [4]. These microorganisms present a major biomass yield and photosynthetic rate compared to higher plants and be grown throughout the year in areas unsuitable for agriculture [9].

Due to these reasons, microalgae are quoted not only for economic and social purposes but also to become an important solution to environmental so necessary and urgent. The microalgae photosynthetic efficiency in crops supplemented with CO_2 can be up to 8.3%, while the photosynthetic efficiency of terrestrial plant species is estimated at 4.6% [6]. Microalgae have the capacity to remove 10 to 50 times more CO_2 than terrestrial plants, due to the higher concentration of chlorophyll per unit area [81]. Through autotrophic growth, approximately 1.83 kg of CO_2 are fixed for each 1 kg of algal biomass [82].

Despite the ability of microalgae to assimilate CO_2 from the atmosphere, its low concentration, added to the low mass transfer coefficient between the air and the surface of the culture medium, make carbon a limiting nutrient for biomass growth [83], therefore, the supplementation with inorganic carbon can increase the biomass production. De Godos et al. [84] evaluated the effect of CO_2 addition during biomass cultivation in swine effluent in high rate algal ponds (HRAP). The addition of gas with 7.5% CO_2 provided a biomass production of 422 mg VSS L^{-1} while the control treatment, without the addition of CO_2, allow obtaining 297 mg VSS L^{-1}. The authors pointed out that the assimilation of CO_2 in microalgae growth is dependent on the limitation of inorganic carbon, which in turn is more evident in conditions of greater radiation and temperature because favor the photosynthesis. Posadas et al. [85] evaluated the CO_2 incorporation in microalgae cultivation in primary domestic sewage through HRAP system. It was obtained a biomass productivity of 17 g m^{-2} d^{-1} with the addition of pure CO_2 (99.9%), while in the cultivation without extra CO_2 addition, was obtained a productivity of 5 g m^{-2} d^{-1}.

Given that the CO_2 concentration in the atmosphere varies from 0.03% to 0.06%, the use of atmospheric emissions from industrial processes may represent an alternative source of CO_2 for the cultivation of microalgae. This practice is directly related to the concept of circular bioeconomy, since it uses waste in a subsequent process, minimizing the emission of pollutants and contributing to reducing costs. Low-cost sources of CO_2, such as furnaces, power plants and flue gases from boilers can be used to feed a microalgae systems [86,87] reducing the CO_2 emitted to the atmosphere. This is yet another economic and sustainable advantage of the microalgae cultivation. The biochemical composition of microalgae, and consequently, their final utilization for the most diverse options uses, is strongly affected by the CO_2 source (origin), quantity and quality. Most microalgae perform well under high CO_2 concentrations such as 15% CO_2 which is the typical concentration of the industrial chimney exhaust flue gases, considering the NO_x and SO_x [88]. Even richer CO_2 environments (up to 50% CO_2) offer also conditions for CO_2 fixing through microalgae as previously reported by Sung et al. [89]. Table 1 presents examples of studies that evaluated alternative sources of CO_2 in microalgae cultivation.

The addition of emission gases must be carried out with adequate control. Emissions from industrial activities can contain pollutants that can be toxic and negatively affect the growth of microalgae. SO_2, hydrolyzed in water, leads to the formation of hydrogen ions, reducing pH, which impairs the growth of microalgae [97]. Chiu et al. [95] studied the production of *Chlorella* during the constant addition of flue gases from the coke oven. The authors observed that the cultivation obtained a biomass concentration of 2.87 g L^{-1} and also contributed to the removal of SO_x and NO_x by 50% and 70%, respectively, using concentrations of 78 ppm NO and 87 ppm SO_2. Radmann et al. [93] evaluated the growth of different species of microalgae under the addition of gases emitted by thermoelectric plants, with 60 ppm SO_2 and 100 ppm of NO. The microalgae *Spirulina* sp. and *C. vulgaris* reached concentrations of 1.59 and 0.98 g L^{-1}, respectively. The species *S. obliquus* reached 0.68 g L^{-1}, while *S. nidulans* obtained 0.41 g L^{-1}.

Despite the microalgae capacity to assimilate CO_2, and the use of atmospheric emissions as potential sources of this gas, this does not mean a reduction in emissions. The CO_2 used will be converted into organic carbon in the microalgae cells. As soon as this biomass is used, the organic matter will be degraded and the CO_2 emission will occur. However, microalgae can be a feedstock for biofuels production and other products in the most sustainable way, minimizing fossil fuel use [83]. In summary, the use of microalgae, compared to conventional methods of gaseous effluents treatment, can have the double benefit of reducing flue gas toxicity and the generation of biofuel and biorefinery byproducts [98], applied in the concept of circular bioeconomy.

2.3.2. Microalgae for wastewater treatment

Environmental benefits from microalgae utilization go beyond GHG assimilation. Koller et al. [99] state the possibility of mixotrophic microalgae cultivation, combining removal of pollutants from wastewater in a heterotrophic phase (assimilation of soluble organic carbon) and generation of high added value products in an autotrophic phase (assimilation of inorganic carbon - CO_2). According to Molinuevo-Salces et al. [100] the supply of nutrients is one of the main barriers for microalgae cultivation on a full scale. The use of wastewater nutrients can be a strategy, that contribute for both bioremediation and the final treatment of wastewater [101].

These microorganisms are capable of developing in effluents with different compositions since they can assimilate the nutrients

Table 1
Results and characteristics of the studies on atmospheric emissions utilization as a CO_2 source for microalgae cultivation.

Microalgae strain	Growth medium	Reactor	CO_2 source	CO_2 concentration (%)	Biomass productivity (g L^{-1} d^{-1})	Reference
Consortium (predominance of *C.vulgaris*)	Domestic sewage after septic tank	HRAP	Exhaust gas of gasoline combustion	5.9	6.12 g m^{-2} d^{-1}	[90]
Nannochloropsis oculata	Synthetic medium	HRAP	Coal-fired power plant	11–14	26.4 g m^{-2} d^{-1}	[91]
Tetraselmis sp.		10L Glass Flasks	Cement flue gas	12–15	0.057	[92]
Spirulina sp.		Tubular Photobioreator	Thermoelectric industry	12	0.08	[93]
Scenedesmus obliquus					0.05	
Synechococcus nidulans					0.04	
Chlorella vulgaris					0.09	
Nannochloropsis gaditana		Flat-Panel reactor	Coal-fired powerplant	10–15	0.078	[94]
Chlorella sp.		Bubble column Photobiorreator	Coke oven Stell	23	0.13	[95]
Desmodesmus abundans		3L Photobioreactor	Cement kiln dust	25	0.227	[96]

present in wastewater. After the separation of the biomass, the effluent is purified and can be released into receiving watercourses or reused into other activities (see Section 2.1). In this context, reactors utilized at the production of biomass from wastewater treatment have been evaluated and improved, such as tubular photobioreactors [102], flat-plat [11], bubble columns [12], and attached growth systems [103]. Considering the context of a WWTP, the HRAPs are the reactors with more consistent results on a large scale [10]. Table 2 presents various studies that explore microalgae potential for wastewater treatment.

HRAPs are open reactors and present much more advantages over conventional pond systems. Its operation occurs through the continuous mixing of the effluent by paddlewheels. Moreover, they are operated through the establishment of a microorganism consortium, mainly microalgae and bacteria, based on the establishment of the symbiotic relationship between them [104]. Through photosynthesis, microalgae produce dissolved oxygen (DO) that is consumed by heterotrophic bacteria in the process of organic matter degradation from the effluent. This process, consequently, releases CO_2 that is used by microalgae in their autotrophic metabolism. Besides the action of heterotrophic bacteria, at night some microalgae exercise breathing, contributing to the degradation of organic matter [110–114].

The removal of nitrogen in microalgae-based wastewater systems is directly dependent on the organism's metabolism. Photosynthetic activity will increase the pH, which in turn interferes with the volatilization of ammonia nitrogen, due to the higher fraction of NH_3. In addition, the production of oxygen may enable the development of nitrifying bacteria in the consortium of microorganisms with the conversion of ammonia nitrogen to nitrite and later to nitrate. This conversion implies a transformation of the nitrogen forms, but not the removal itself. Another possibility for the removal of nitrogen is the assimilation of inorganic forms such as ammonium, nitrite and nitrate, throughout the growth of biomass. Ammonia nitrogen is the primary source of assimilation because it occurs through passive diffusion, increasing proportionally the absorption rate with the concentration of the substrate [105]. On the other hand, the assimilation of nitrate has a maximum level with an increase in the concentration of the nutrient. However, nitrate provides an extension of the exponential growth phase, through the surplus metabolic capacity in the amino acid synthesis [105]. Couto et al. [106] evaluated the mechanisms of nitrogen removal in HRAP treating UASB reactor effluent, being found that nitrification and assimilation by biomass were the main forms of nitrogen transformation/removal. Gonzalez-Fernández et al. [107] discovered that nitrification was the main process for $N{-}NH_4^+$ transformation during the cultivation of microalgae in anaerobic effluent. Since this effluent is composed of non-easily biodegradable organic matter, the available DO was primarily used in nitrification, rather than in the degradation of organic matter.

The removal mechanisms are directly related with the recovery of nutrient resources in the effluents. The removal by volatilization, for example, may allow reaching the regulation standards, however, without allowing the use of the nutrient in another production cycle. Thus, strategies of system control (i.e. CO_2

Table 2
Microalgae potential for wastewater treatment.

Effluent	Microalgae strain	Reactor	Efficiency removals (%)			**Biomass productivity (g TSS m^{-2} d^{-1})**	Reference
			Nitrogen	Phosphorus	Organic Matter		
Rural streams with nutrient pollution	Consortium: *Spirogyra* sp., *Cymbella* sp and *Navicula* sp.	HRAP (20 m^2) with filamentous algae matrix	18% of TN	65.8% of TP and 68.1% of PO_4^{3-}	−32.8% of total COD	-	[102]
Primary settled domestic wastewater	Consortium: *Mucidosphaerium pulchellum* (85% of abundance)	HRAP 20 cm depth (2.23 m^2) with CO_2 addition	69.3 −78.9	19.2–34.3	-	2.1–10.1	[103]
		HRAP 30 cm depth (2.23 m^2) with CO_2 addition	63.6 −77.4	16.2–33.8	-	3.5–10.1	
		HRAP 40 cm depth (2.23 m^2) with CO_2 addition	58.5 −75.8	11.6–26.7	-	4.8–13.4	
Primary settled domestic wastewater	Consortium: *Micractinium* sp. and *Desmodesmus* sp.	HRAP (1.25 ha) with CO_2 addition	5.6 −67.4	14.0–24.4	81.8–92.1% of dissolved BOD_5	4.4–11.5 g VSS m^{-2} d^{-1}	[97]
Brewery wastewater	*Scenedesmus obliquus*	Bubble column PBR (5 L)	67–97	13–26% of orthophosphate	55–74	80.5–224.3 g VSS L^{-1} d^{-1}	[104]
Livestock wastewater	*Chlorella* sp. *and Phormidium* sp.	Algal biofilm reactor (630 cm^2)	98% of TAN	93% of TDP	87	105	[105]
Landfill leachate	*Chlorella vulgaris, Spirulina* sp., *Scenedesmus quadricauda,*	HRAP (0.27 m^2)	94.3 −98.7	49.3–85.6% of PO_4	69.4–90.7% of COD	9.2–26.3 g VSS m^{-2} d^{-1}	[106]
Pre-treated diluted swine manure	Consortium: *Chlamydomonas, Chlorella* and *Nitzschia*	HRAP (1.5 m^2)	62–88% of TKN	-	57 - 67 of COD	5.7–27.7 g m^{-2} d^{-1}	[107]
Effluent	Microalgae strain	Reactor	Efficiency removals (%)			**Biomass productivity (g TSS m^{-2} d^{-1})**	Reference
			Nitrogen	**Phosphorus**	**Organic Matter**		
Domestic sewage after facultative pond	Consortium: *Cyanophyceae Chlorophycean (Micractinium sp., Pediastrum sp., Oocystis sp., Scenedesmus sp.)*	HRAP (223 m^2)	76.5	17.17% of orthophosphate	36.63 of BOD_5	15.8	[108]
		HRAP (223 m^2) with CO_2 addition recovered from biogas	68.8	16.7% of orthophosphate	48.89 of BOD_5	14.1	
Domestic sewage after UASB reactor	Consortium: *Chlorella* sp. (34% of abundance) *Desmodesmus* sp. (36% of abundance)	HRAP (3.3 m^2)	71	14	52	11.4 g VSS m^{-2} d^{-1}	[109]
	Consortium: *Chlorella* sp. (40% of abundance) *Desmodesmus* sp. (46% of abundance)	HRAP (3.3 m^2) after UV disinfection	74	19	55	9.3 g VSS m^{-2} d^{-1}	

TN = total nitrogen; TAN = total ammonia nitrogen; TP = total phosphorus; SP = soluble phosphorus; TDP = total dissolved phosphorus; DRP = dissolved reactive phosphorus; COD = chemical oxygen demand; BOD_5 = biochemical oxygen demand; TSS = total suspended solids; VSS = volatile suspended solids.

supplementation through pH control to minimize nitrogen loss through volatilization) can increase the possibility of recovering this resource.

Phosphorus removal will occur by chemical precipitation, with high pH values, or by biomass assimilation. Similarly, to the nitrogen, pH control can assist in the higher rate of phosphorus assimilation by biomass and consequently allow the recovery of this nutrient. Phosphorus participates in the transfer of intracellular energy and nucleic acid synthesis, in addition to the cell division reactions [105], being a fundamental nutrient for cell growth. There are various studies that reporting a high efficiency of P removal via biocapture using microalgae grown in domestic [115–117], industrial [118], or agro-industrial [11,119] wastewaters. However, phosphorus removal in algal systems may be often difficult, as could be observed in Table 2 with most results inferiors to 35% of removal efficiency. Algal biofilm reactor that presented a P removal of 93% was one of the exceptions, explained by algal biofilm P assimilation, as pH did not exceed the 7 value [111]. On the other hand, Assis et al. [103] studied domestic sewage treatment through a hybrid algae system, composed of a HRAP and a biofilm reactor, observed 21 and 25% removals of soluble phosphorus, in systems with and without CO_2 supplementation, respectively. These results may indicate that even algae attached growth systems may have limitations for P removal, mainly, those related with the lowest amount of P necessary for the cellular composition of microalgae. P luxury uptake is an alternative to increase P removal via assimilation, and can lead to an increase in cell P content up to 4–6% DW, when in normal conditions P content is about 1% [120]. In view of the concern with the mineral reserves of phosphorus, previously mentioned in Section 2.2, microalgae can be a tool for the recovery of this nutrient in several effluents.

In addition to nutrient removal, the inactivation of pathogenic organisms can be obtained through microalgae growth systems. Photosynthetic activity will raise the pH and DO concentrations and these factors can act synergistically for the occurrence of microorganisms photo-oxidation [121]. The surface area/volume ratio is a design parameter for wastewater treatment and microalgae cultivation directly related with the inactivation efficiency of pathogenic bacteria. In theory, the greater this parameter, the greater the exposure of the culture medium to solar radiation, the greater the photosynthetic activity, and consequently the greater the efficiency of inactivation. Craggs et al. [122] evaluated HRAPs with 30 cm and 45 cm deep, with different surface areas and with the same volume, achieved better disinfection efficiency for HRAP with the greater area and less depth. Rich DO environments, together with intense radiation, can provide the formation of atomic oxygen and/or superoxide oxygen that cause irreversible damage to the microorganism's DNA [123]. Ansa et al. [121] evaluated the effect of algal biomass in the removal of total coliforms in domestic sewage, verifying that in the absence of light, the decay was greater with an increase in chlorophyll-a concentrations, may have been the reason, the release of substances by microalgae, which have a biocidal effect and act in the inactivation of coliforms. Molina-Cárdenas et al. [124] observed that in a batch culture, the concentrations of bacteria were reduced to undetectable levels in 2–7 days, due to microalgae *I. galbana* synthesis of antibacterial fatty acids that inhibit the development of pathogenic bacteria.

Currently, there is a concern with the presence of several emerging microcontaminants, like those in medicines, pesticides and endocrine disruptors that are accumulated in the wastewater. These compounds are persistent and can lead to bioaccumulation [125]. Some studies indicated the possibility of removing these compounds in microalgae cultivation systems. Vassalle et al. [126] investigated the removal of microcontaminants in HRAP and showed 64%–70% of removal efficiencies for drugs, such as ibuprofen, diclofenac, naproxen and paracetamol. The study also reported efficiencies of 90–95% in removing estrogens. Results may be justified due to the processes of direct photodegradation, bioadsorption and biodegradation. Abargues et al. [125] showed that the treatment with oxygen supersaturation via microalgae photosynthesis presented a higher degradation rate of endocrine disruptors when compared with the treatments without microalgae.

Another group of interest in the wastewater treatment is the trace metals. As they are not biodegradable, similarly to emerging microcontaminants, the trace metals persist in the environment, also leading to bioaccumulation in the food chain, which can trigger critical environmental and health problems [127]. Molazadeh et al. [128] evaluated the Pb removal by *Chaetoceros* sp. and *Chlorella* sp. and obtained removal efficiencies of 60% and 78%, respectively. The authors point out that efficiency will be dependent on parameters such as pH, temperature and contact time. The presence of trace metals in algal biomass can represent a challenge for its later use. Leong and Chang [129] highlighted the necessity of techniques development for biomass pretreatment with the objective to recover metals as a strategy to overcome this bottleneck.

3. Microalgae the green treasure: bio-based products and biofuels

Microalgae are a promising green feedstock for several products, i.e., animal nutrition, bioplastics, bioinks, biofertilizer, biofuels and bioenergy [130] (Fig. 3).

Regarding bioenergy, various biofuels can be produced from algal biomass, such as methane, syngas, hydrogen, ethanol, biodiesel, jet fuel, bio-char, bio-oil, among others [5,131] (Fig. 4). According to Medeiros et al. [87], biofuels based on microalgae biomass may have a crucial role in bioenergy production in the future.

Microalgae biodiesel production is justified by the ability of some species to accumulate high concentrations of lipids [132]. *Chlorella* and *Scenedesmus* strains were reported to accumulate 30.3% and 35.7% of lipids (dry base) in its composition [133]. In comparison with oilseeds commonly used for this purpose, microalgae have several advantages such as not requiring agricultural areas for its production and can be cultivated throughout the year. Productivity per unit area can reach up to 10,000 L ha^{-1} $year^{-1}$ of biodiesel [134], being by far higher than the capacity that presents other oil sources such as sunflower, canola, soy, *Jatropha*, palm, among others [5] (Table 3). Moreover, compared with other biofuels, biodiesel can be an immediate and applicable alternative for fossil-based diesel.

However, the lipid content stored in the microalgae cells can vary greatly between different species and even in the same species, depending on the culture conditions. Many different key conditions for high lipid accumulation in microalgae are studied in the literature. Generally, nutrient deprivation conditions lead to a greater accumulation of lipids by microalgae, such as the limitation of nitrogen and phosphorus [138–140]. Other conditions, i.e. stress from cadmium, iron and salinity contents, light intensity and the silica concentration (in the last case of marine diatoms) [139,141] also influence biomass growth and consequently, it is a process lipid accumulation with a high energy-intensive. Among nutrient starvation tests (N, P and Fe), Srinuanpan et al. [142] concluded that N starvation was the most efficient in increasing lipid content just like its saturation level in biomasses *S. obliquus* and *M. reisseri.* Usual steps for oil obtaining from microalgae can be cited as harvesting, biomass drying and oil extraction. Among them, the drying process can be considered a bottleneck, since it is a process with a high energy-intensive [143]. Therefore, lately, biodiesel production from wet microalgae biomass has gained attention [144]. In Table 4,

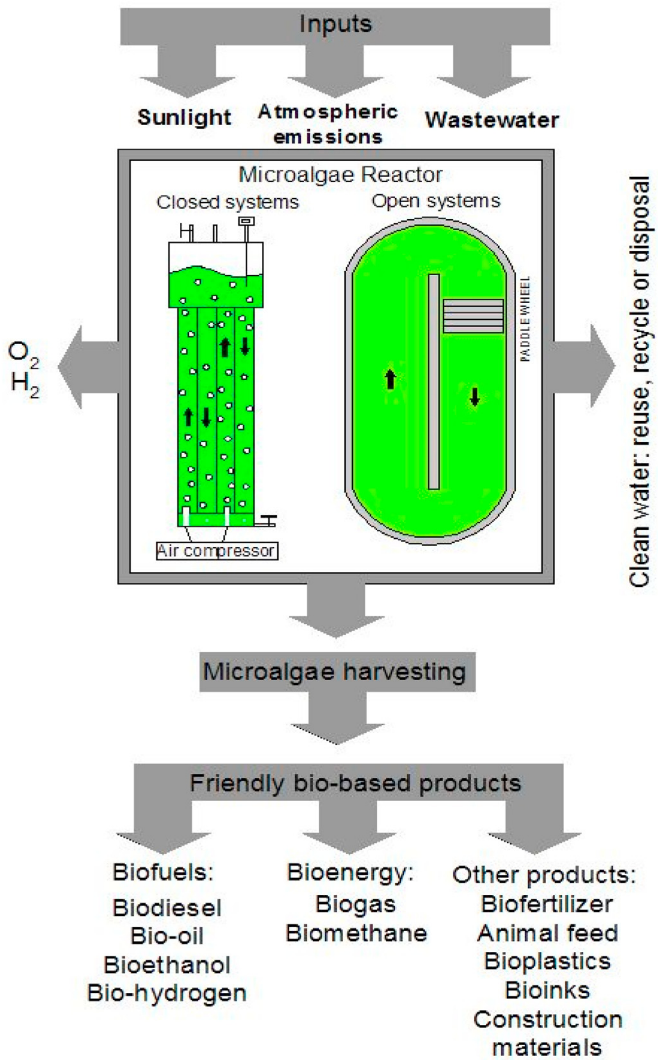

Fig. 3. Bioproducts and biofuels obtained from wastewater treatment using microalgae.

successful cases in the production of biomass and lipids were selected through the cultivation of microalgae in synthetic medium and also in several wastewaters. It can be observed that the wastewater is an excellent cultivation medium for dozens of microalgae species. The values recorded using artificial culture media are comparable to those using wastewater for the growth of species.

An important strategy to maximize the production of the lipids in microalgae biomass is the increase of salinity in the culture medium [152]. Most freshwater microalgae can be grown in salinities between 2 to 18 ppt [162]. Some marine strains can be successfully grown in salinity ranges between 12 and 40 g L^{-1}, being the optimal range between 20 and 24 g L^{-1} [163,164]. In a study by Salama et al. [165] found that the increase in salinity from 0.43 to 25 mM increased the percentage of lipids in the biomass of *C. mexicana* and *S. obliquus* from 23% to 37% and 22%–34%, respectively. These results showed the importance of salt stress to maximize the lipid percentage in green microalgae cells. Abomohra and Almutairib [166] cultivated *Scenedesmus obliquus* in anaerobically digested seaweeds (*Gracilaria multipartita*), that registered a maximum dry weight of 4.57 g L^{-1} with 28.8% of total lipids. The study of these authors showed the highest lipid productivity and FAMEs recovery (65.2 mg L^{-1} d^{-1} and 123.3 mg g^{-1} dry weight, respectively), with enhanced biodiesel characteristics.

Another methodology used to maximize biodiesel production from *Scenedesmus obliquus* biomass was the application of night lighting using monochromatic light-emitting diodes [167]. In this case, the growth of microalgae, the production of lipids and the recovery of biodiesel increased significantly under the combination of blue-red lighting. The average lipid volumetric productivity recorded under the reported conditions was 58.3 mg L^{-1} d^{-1} and the total FAME was 147.2 mg g^{-1} (dry weight).

Lee et al. [168] investigated the conversion of fats, oils and greases (FOGs) into fatty acid methyl esters (FAMEs) without pretreatment. The process was thermally induced to perform the simultaneous esterification of free fatty acids (FFAs) and lipid transesterification containing high concentrations of impurities in the biomass (≈14 wt%). The maximum FAMEs yield recorded by the authors was >86%, based on the mass of the raw material without removing the impurities. This study proved that this technique can be considered valuable and effective for converting low-quality raw materials contained in FOGs into biodiesel, being recommended to maximize processes for obtaining this biofuel.

Almarashi et al. [169] used low doses of cold atmospheric-pressure plasma (CAPP) as pre-treatment of inoculum for cultivation *Chlorella vulgaris*. The authors reported high performance in the biodiesel recovery. The highest recorded lipid concentration was 20.99% and lipid productivity was 40.7 mg L^{-1} d^{-1}, when the inoculum was exposed to CAPP for 30 s before cultivation. The maximum FAMEs recovery of 478.7 mg g^{-1} (dry weight) was observed at pretreatment for 60 s, being considered to the greater recovery in biodiesel in this condition due to plasma stress. The results found by the authors indicate that the recovery of FAMEs, as well as the quality of biodiesel, were improved by the CAPP treatment when compared to other traditional methods.

Biodiesel production from microalgae focuses on the use of lipid content. After its extraction, the remaining biomass can be used for other purposes, meeting the context of circular economy green and increasing the economic value of the biomass. Ma et al. [132] demonstrated that the microalgae residual after wet microalgae *Chlorella vulgaris* lipid extraction could be used for fermentable sugar production through enzymatic hydrolysis of the carbohydrate. Assemany et al. [170] evaluated the use of residual biomass after lipid extraction as a substrate in the anaerobic digestion. The results showed a biogas production potential of 2.6 m^3/kg VS (volatile solids), higher than the biogas production from raw biomass. According to the study, lipid extraction promoted the disruption of microalgae cells, facilitating the degradation of organic matter by anaerobic microorganisms. These results highlight the possibility of synergistic effects between different biofuel production techniques.

Biogas is the most promising biofuel that has the potential to mitigate the current negative impacts of fossil fuels utilization, mainly energy crisis and climate change [171]. Biogas production occurs through anaerobic digestion, performed by a consortium of bacteria and *archeas* in the biochemical conversion of the organic matter into bioenergy, more specifically, CH_4 [172]. Methane gas can be converted into renewable transportation fuels or into electricity. The digestate, comprised of nutrients and water can be reused in other production processes, such as algae cultivation, or used as a biofertilizer. In the context of bioenergy production from algal biomass and fighting over contamination, this process represents an important alternative, especially caused for the wet biomass, minimizing the costs of harvesting and drying steps.

Methane yield from microalgae can vary a lot, depending on algae species, i.e., from 0.17 m^3 kg^{-1} VS for *Chlorella minutissima* biomass to 0.54 m^3 kg^{-1} VS for *Macrosystis pyrifera* (brown

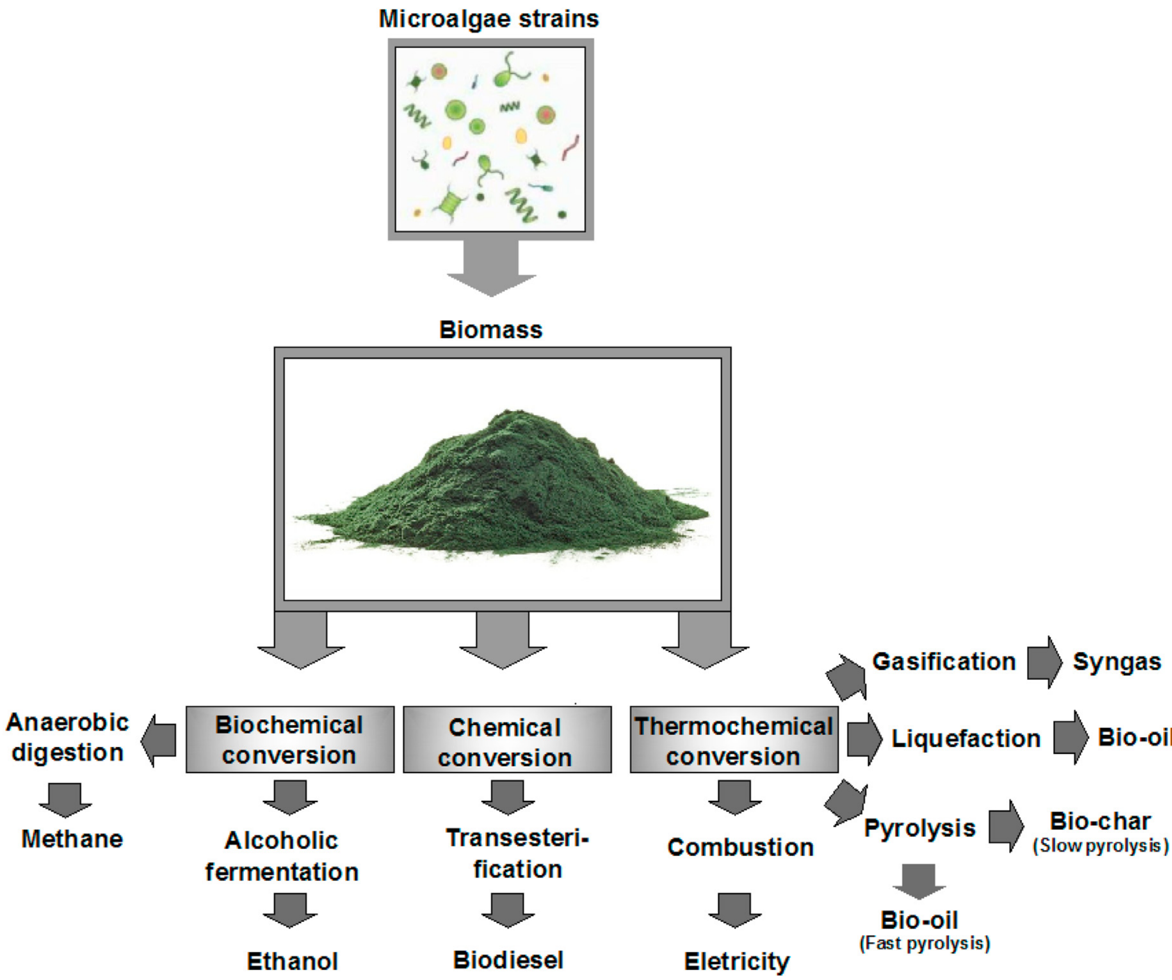

Fig. 4. Routes for converting microalgae biomass into biofuels.

Table 3
Comparison of some sources of biodiesel: terrestrial crops *vs* microalgae [82,135–137].

Crop	Oil yield (L ha^{-1} yr^{-1})
Corn	172
Hemp	363
Cotton	325
Soybean	446
Mustard	572
Camelina	915
Seed	952
Sunflower	1,190
Castor	1,307
Canola	1,892
Coconut	2,689
Jatropha	5,950
Oil Palm	12,000
Microalgae (low oil)	58,700
Microalgae (medium oil)	97,800
Microalgae (high oil)	136,900

macroalgae) [173]. But biogas yield from microalgae remains close or higher than the yield of other biomass types, such as sugar crops (0.19 m^3 kg^{-1} VS) and lignocellulosic biomass (0.17 m^3 kg^{-1} VS) [174]. However, there are still some key technoeconomic limitations, particularly the low anaerobic biodegradability and the reduced C/N ratio of algal biomass [175]. In this sense, pretreatment strategies for cell wall rupture, and co-digestion, have been widely studied (Table 5).

Regarding energetic feasibility, anaerobic digestion from microalgae biomass proved to be rentable. Chao Xiao [186] reported that all tested methods of biogas production obtained a positive energy gain, with net output energy of 1.73, 2.37, and 3.11 kWh, from the anaerobic processes without pretreatment and with hydrothermal pretreament moved without and with solar-driven, respectively. When using the co-digestion strategy, net energy production was 3.2 GJ per day versus 1.6 GJ per day for microalgae mono-digestion, indicating a generation of 2.7 and 4.5 fold the energy consumed. If this potential energy would be transformed into electricity via cogeneration, 151 and 307 kWh per day could be provided by the mono and co-digestion process, respectively [177]. Vassalle et al. [183] also obtained a positive net energy ratio of 2.8 through co-digesting microalgae biomass and domestic sewage in a UASB reactor, that represented a 180% energy gain in relation to the consumption. This energy gain was 5 times greater when compared to the sewage mono-digestion.

Hydrothermal liquefaction (HTL) is a thermochemical process of organic matter conversion, under subcritical conditions of temperature and pressure. Four different products are generated from biomass conversions, such as the bio-oil, gas, solid waste and water-soluble compounds. Due to severe operating conditions, the entire organic fraction is degraded, and bio-oil is not only produced from the lipid content, but also from carbohydrates and proteins [4]. Moreover, HTL occurs in aqueous media, avoiding energy

Table 4
Lipid potential production from microalgae biomass.

Substrate	Reactor	Strains	Light (μmol m^{-2} s^{-1})	Light source	Biomass concentration (g L^{-1})	Biomass production (g L^{-1} d^{-1})	Lipid production (g L^{-1} d^{-1})	Reference
Synthetic culture medium								
Bold's Basal Medium	Flasks	*Chlorella* sp. (UMACC050)	40	Artificial	NR	0.60	0.229	[145]
Synthetic medium (Z)	Flasks	*Chlorella* sp.	≈80[a]	Artificial	0.594	1.44	0.1901	[146]
		Planktothrix isothrix			0.640	0.28	0.0168	
		Synechococcus nidulans			0.401	0.20	0.0272	
Synthetic medium (WC)		*Scenedesmus acuminatus*			0.640	0.42	0.0571	
		Pediastrum tetras			0.528	0.36	0.0623	
		Chlamydomonas sp.			0.536	0.39	0.0834	
		Lagerheimia longiseta			0.460	0.21	0.0239	
		Synechococcus nidulans			0.560	0.69	0.0938	
		Monoraphidium contortum			0.296	0.15	0.0298	
Synthetic medium (C)	Flasks	*Sinechocystis sp.*	≈80[a]	Artificial	1.295	0.39	0.0542	[146]
		Romeria gracilis			0.542	0.22	0.0244	
		Aphanothece sp.			0.458	0.29	0.0299	
Synthetic medium	PBR	*Chlorella minutissima*	NR	Internal light (Blue LED)	0.044–0.0625	0.062	0.0057–0.0089	[147]
Artificial seawater f/2 medium	Airlift PBR	*Chlorella minutissima 26a*	133	Artificial	NR	0.1886	0.0928	[148]
Synthetic medium BG11	BC-PBR	*Chlorella* sp. FC2 IITG	100-1,700	Natural sunlight	8.6	1.4	0.753	[149]
Wastewater culture medium								
Municipal wastewater (Centrate)	Biocoil	*Chlamydomonas reinhardtii*	220	Artificial	NR	2	0.505	[150]
Municipal wastewater Secondary	Flasks	*Chlorella vulgaris*	≈140	Artificial	1.03	0.1665	0.04138	[151]
Municipal wastewater Secondary (75%) + primary (25%)					1.11	0.13876	0.04559	

[a] Original article was written in kLux; [b] Original article was written in μE m^{-2} s^{-1}; PBR - Photobioreactor; BC-PBR - Bubble Column Photobioreactor; PSBR - Porous substratum biofilm reactor; SBR - Bench scale sequencing batch reactor; FPCP - Flat-Plate Continuous Photobioreactor; HRP - High rate ponds; MPBR - Membrane Photobioreactor; BCPBR - Vertical bubble-column photo-bioreactor; NR – Not reported.

requirement for biomass drying. These characteristics make HTL an attractive technology, that may overcome some bottlenecks associated with biofuels production from microalgae biomass, especially the wastewater grown microalgae biomass with low lipid content. HTL's bio-oil yield is related with the operational conditions, such as temperature, reaction time, water ratio in the biomass, pressure and the presence of catalysts. Table 6 shows some examples of HTL process using microalgae biomass.

HTL can be inserted in a circular bioeconomy context through the valorization of its by-products. The gases generated are mostly composed of CO_2, which can be used in microalgae cultivation [7] or like additive in the materials utilized in the construction sector. Solid wastes, due to their majority constitution of ashes, can be destined to asphalt pavement [187]. Water-soluble products, on the other hand, are composed of organic acids and nutrients that can again be used in other microalgae cultivation [188,189] or even as a substrate for anaerobic digestion [190,191]. However, the aqueous phase has compounds that can be toxic to the microorganisms, such as aromatic compounds and metals [192]. Thus, its use should be evaluated based on dilutions that do not cause inhibitory effects on microalgae growth.

Although HTL is an attractive process for bio-oil obtention through algal biomass conversion, regarding resource recovery in the context of a circular economy, there are still challenges to be faced. Some main points are the high N content in bio-oil, due to the composition of biomass [75], the presence of ash, especially when the biomass comes from wastewater [193], the expansion of the scale of reactors and its continuous operation, as well as a better understanding of operational parameters such as heating rate, initial pressure and particle size [194].

In addition to the processes presented in Fig. 4, lipid conversion into supercritical fluids (SFE), as presented in Table 7, can have advantages over conventional processes [2]. SFE makes use of high pressures and temperatures in a fluid to break cells without additional chemical reagents (or minimizing their use). This method has been proven to be extremely time-efficient with high yields [203], enabling fast conversion of lipids into biodiesel (20 and 60 min), whereas solvent extraction can take up to 24 h. Another advantage of the method is that the use of a catalyst can be avoided, eliminating the production of pollutants. Higher temperature and pressure, combined with the effect of the supercritical solvent, break the cell walls and facilitate the diffusion of the solvent in the cell matrices with a much higher degree of efficiency than conventional [2,204]. On the other hand, the main disadvantage of SFE is the greater capital necessary, including the operational cost due to high temperatures and pressure requirements [204].

Table 5
Microalgae potential for biogas production and strategies applied for yield improvement.

Microalgae strain	Growth medium	Reactor and conditions	Pretreatment	Co-digestion	**Biogas yield (m^3 CH_4 kg^{-1} VS)**	Reference
***Chlorella* sp. (61.2% abundance)**	Chicken manure	100 mL flasks, 36 °C, batch	No	No	1.44 mL g^{-1} d^{-1}	[176]
***Chlorella* sp.**	Domestic sewage	2L CSTR, 37 °C, HRT = 20 days	No	With primary sludge	0.33	[177]
				No	0.20	
***Scenedesmus* sp.**	Domestic sewage	12.4L AnMBR, 35 °C, HRT = 15–50 days	No	No	0.17 m^3 CH_4 kg^{-1} COD	[178]
***Chlorella* sp.**		12.4L AnMBR, 35 °C, HRT = 30 days			0.24 m^3 CH_4 kg^{-1} COD	
***Scenedesmus* sp.**		14L AnMBR, 35 °C, HRT = 15–50 days		With primary sludge	0.21 m^3 CH_4 kg^{-1} COD	
***Chlorella* sp.**					0.23 m^3 CH_4 kg^{-1} COD	
***Scenedesmus* sp.**	Domestic sewage	14L CSTR + AnMBR, 39 °C, HRT = 7–28 days	No	No	0.185	[179]
		14L AnMBR + CSTR, 39 °C, HRT = 30 days			0.36	
		14L CSTR + CSTR, 39 °C, HRT = 15 days			0.305	
***Chlorella* 1067**	Chicken manure digestate	200 mL CSTR, 35 °C, batch	No	No	0.14	[180]
				With chicken manure	0.24	
***Chlorella* sp.**	Synthetic BG11 medium	500 mL flasks, 35 °C, batch	Enzymatic + lipid extraction	No	0.13	[181]
				With grass	0.17	
Scenedesmus obliquus	Brewery wastewater	2.8L Hybrid ascending reactor, 37 °C, HRT = 6 days	No	No	0.08	[182]
				With olive mill wastewater	0.25	
			Thermal		0.21	
***Kirchneriella* sp.**	Domestic sewage	343L UASB, environmental conditions, HRT = 7 h	No	No	0.15	[183]
				With primary domestic sewage	0.21	
***Chlorella* sp. and *Scenedesmus* sp.**	Synthetic wastewater	160 mL flaks, 35 °C, batch	No	No	0.26	[184]
			Thermal + alkaline		0.33	
***Stigeoclonium* sp., *Monoraphidium* sp., *Nitzschia* sp. and *Navicula* sp.**	Domestic sewage	160 mL flaks, 35 °C, batch	No	No	0.11	[185]
			Thermal		0.181	
			Hydrothermal		0.135	
			Microwave		0.128	
			Ultrasound		0.114	

CSTR = continuous stirred tank reactor; AnMBR = anaerobic membrane bioreactor; UASB = upflow anaerobic sludge blanket reactor; HRT = hydraulic retention time; VS = volatile solids.

Table 6
Operational conditions and bio-oil yield in different studies of microalgae HTL.

Microalgae strain		Biomass composition (%)				Operational conditions				Boi-oil yield (% dry basis)	Reference
	Growth medium	Protein	Sugar	Lipid	Ash	Temperature (°C)	Time (min.)	Percentage of solids	Catalyst		
Consortium	Natural Lake	78.5	11.7	6.7	-	350	120	4	HZSM-5 zeolite	1600	[195]
	Wastewater	28.3	5.4	23.3	40.0	300	15	10	NA	44.4(a)	[75]
		27.2	23.6	1.7	47.5		60	25		49.9(a)	[187]
		48.6	11.1	7.8	25.9	350	120	6.6	HZSM-5 zeolite	58.0	[196]
Scenedesmus obliquus		54.6	-	12.3	11.5	300	60	7	NaOH	24.6	[197]
Nannochloropsis	Synthetic medium	36.4	12.4	19.0	8.91	275	30	01:10	-	31.4	[198]
		40.5	-	21.9	4.4	250	60	6	-	28.9	[199]
N. gaditana		43.8	15.7	35.5	4.5	320	10	01:10	CaO	49.7	[200]
C.vulgaris		61.8	26.7	2.3	8.7	350	Heating rate of 10 °C.min^{-1} min. Removed when	5.5–6.8	-	42.1	[201]
Spirulina		70.2	19.3	1.1	7.7		it reached reaction temperature			36.2	
G. sulphuraria	Wastewater	41.0	10.5	5.8	42.0	350	6	5	-	28.1	[202]

4. Think global, act local: how microalgae can fit in?

"Think global and act local" is a slogan initially develop in Rio Earth Summit, the second Conference of the United Nations held in Rio de Janeiro, Brazil in 1992, that culminated with the creation of Agenda 21. This document is an instrument of participatory planning in which the responsibility of governments to promote environmental programs and projects is explicitly accepted through policies aimed at social justice and the preservation of the environment [214]. Agenda 21 has a hierarchical spatial scale strategy based on sub-global, national and locally settled plans - Local Agenda 21 [214]. The formulation and implementation of public policies are encouraged, through participatory methodology, that produces an action plan to reach a desirable future scenario for the local community [215] and that takes into account the analysis of vulnerabilities and potential of its basis economic, social, cultural

Table 7
Microalgae biomass conversion by supercritical processes.

Strain	Supercritical condition	Biodiesel yield (%)	Reference
Scenedesmus sp.	SC−CO_2: Lysozyme treatment +50 °C, 500 bar, 13 mL min^{-1}, 30 min	12.5 (dw)	[205]
Scenedesmus obliquus	SC−CO_2: Bead beating + 60 °C, 306 bar, 65 °C, 30 MPa, 5% ethanol co-solvent, 90 min	18.15 (dw)	[206]
Nannochloropsis sp.	SC−CO_2: 50 °C, 200 bar and 24 h	62	[207]
Nannochloropsis (CCMP1776)	Methanol to biomass (12:1): 1200 psi, 30 min	85.75	[208]
Nannochloropsis gaditana	Supercritical methanol to algae ratio (10:1): 255–265 °C, 50 min	45.8 (FAME)	[209]
Nannochloropsis gaditana	Methanol to wet biomass (vol. dw.$^{-1}$) ratio 6:1: temperature 225 °C, 90 min	59.28	[210]
Nannochloropsis sp.	Methanol to algae ratio (10:1) at supercritical conditions: 265 °C, 50 min	21.79 (dw)	[211]
Chlorella protothecoides	Methanol to oil ratio (19:1): 320 °C, 152 bar, 31 min	90.8	[212]
Chlorella vulgaris	Supercritical methanol without catalyst and in the presence of TiO_2 and $SrTiO_3$ nanocatalysts, 270 °C, pressure range of 9–10 MPa, 60 min	16.65 mg g^{-1} (FAME)	[213]

SC−CO_2 = reaction in supercritical CO_2; dw = dry weight.

and environmental.

"Think global, act local" is often used to support small improvements on current environmental sustainability practice. However, a systemic change is highly required in order to meet the scale of the challenges, at neighborhood, city, regional, national and worldwide levels [216]. In addition, progress should be measured in sustainability and should be within environmental limits of the planet, as humankind are on a path to overcome them [216]. Sustainability has three main pillars - environment, society and economy. On a small scale, thinking about eco-cities, there are some challenges to be included in a sustainability local environment, which can broader positive impact in the frontiers, and microalgae can fit in many of them. A city can be sustainable based on how technologies and policies are mobilized to enhance energy, water, healthcare, mobility, security, economic development and community engagement [217].

Transportation is a major concern in urban environments related with air pollution and GHG emissions, however, the microalgae can be a sustainable option for biofuel production. Public and collective transport can be moved with green fuel, such as biodiesel [218,219] and biogas [180,182] from algae biomass (see Section 2.3.3 for more detailed examples). Moreover, thermal energy for house heating can also be obtained, contributing to affordable and safe housing. Residual biomass can, in addition, serve as raw material for construction materials, helping to save resources and to build environmentally friendly buildings. Irfan et al. [220] studied how to optimize bio-cement production using *Chlorella kessleri* microalgae as a source of calcium through a waste feedstock from cement kiln dust. According to the authors, the study of microalga role in the production of bio-cement can result in the readiness of this process in civil construction, besides helping in the environmental pollution mitigation by waste utilization.

In line with Sections 2.1 and 2.2, the promotion of recycling and resource conservation is among the best practices to be included in helping reducing pollution. This involves more efficient use of resources and even, significantly, reduction in resource consumption. Besides achieving zero waste, there is a need to change consumer choices and production relationships throughout the supply chain, which theoretically will become more localized and regionalized [216]. With multiple use characteristics, algae biomass may support resource recovery, especially avoiding the generation of waste during wastewater treatment. Nutrient-rich algae biomass may have various utilities, such as being a feedstock for a bio-based economy, i.e. in the production of bioplastics. Rocha et al. [221] studied the potential of bioplastics production from microalgae consortium from wastewater concluded that despite promising result had been achieved, large-scale microalgae biomass should be better development. Moreover, the mechanical properties of this type of bioplastics deserves improvement, as it limits the product application compared with other available bioplastic options. According to the authors, further strategies, such as composites and crosslinking, should be addressed.

Regarding wastewater treatment, microalgae when used, play an important role in recovering river water quality and enhancing whole urban ecosystems to provide a healthy place for fauna, flora and people co-existence. Several studies cover the wastewater treatment using microalgae, i.e. treatment of domestic sewage [90,115], agro-industrial effluents [11,111,222] and industrial effluent [12,118], see Section 2.3.2 for more detail. Recovered rivers are integrated in the city landscape, supporting the health and leisure of urban populations, while promoting a deeper connection with nature. Restoration initiatives for damage environments, as well as support for local agriculture, urban greening and community gardening are other of the characteristics of an eco-city [223,224].

In terms of food systems, Moloney [216] stated that people should understand and direct experience food growing, in order to obtain a low impact or even zero carbon food. Microalgae biomass will increasingly help to move beyond zero carbon emissions, in line with ecologically sound economic activities. In the context of organic and local agriculture, the kind of soil fertilizing is of great importance and that's where, among others, microalgae biomass can fit in. Nutrient-rich microalgae biomass may be a sustainable source of biofertilizer, helping to reduce the environmental impact of the traditional fertilizers production process and to economize resources. Studies have proved the benefits of using microalgae as a biofertilizer [225], for soil fertility improvement and plant growth, when used as a source of nitrogen [78] or together with triple superphosphate in order to create an environmentally friendly fertilizer [226]. Moreover, grain yield and fruit quality and nutritional characteristics were improved [227], and heterotrophic activity of the soil, besides bacterial growth were stimulated using *Chlorella* sp. suspension [228]. Another possibility is to use microalgae as a source of protein in the human or animal diet, considering that microalgae cultivation is less impactful than the cultivation of terrestrial plants, mainly with regard to soil change and, consequently, GHG emissions. Lamminen et al. [229] studied microalgae as a source of protein supplement in the lactating dairy cows nutrition and their results suggested the suitability of non-defatted and protein-rich microalgae, compared to soya bean protein meal. Favorable results were found in milk fat concentration when *Spirulina* was used, while *Nannochloropsis* offered a most suitable omega-6:omega-3 ratio for human nutrition. However, the authors highlighted poorer palatability of microalgae concentrates.

To finalize, social aspects that go beyond environmental conservation are needed. It is required a transformation through a greater connection between people and the environment, mainly through improvements in health conditions, well-being and social and economic inclusion.

5. Microalgal biorefineries all over the world

Currently exist an increasing worldwide interest in microalgae crops. This factor is manifested in several areas such as bioenergy for the production of biofuels (green crude oil, gasoline, biodiesel, jet fuel, bio-oil, ethanol, biogas, syngas, methane, among others), in the capture and sequestration of CO_2 from several industrial applications like power plant, fermentation plants, cement producers and others, for wastewater purification, production of a wide diversity of products like food supplements (including feed and pet foods), cosmeceuticals, pharmaceuticals, biologicals, chemicals, biochemicals, biomaterials, among others.

Table 8 lists some companies that produce different products from algae biomass with a significant scale under an integrated strategy in the frame of biorefineries. The list is ordered by continent and country.

6. Market: Current microalgal commercial producers

Worldwide, there are many companies that produce microalgae for the development of the research area (including the study of new species) as raw material to produce a variety of products or to be sold to other companies. At a global level, the continents that show the greatest evolution in this matter are America (mainly the United States of America) and Europe, being Portugal a strong player in this sector.

Every year, approximately 7,000 t of dry algae are produced all over the world, being the global market of algae biomass can be estimated at USD 3.8 to 5.4 billion [231]. These numbers reflect that the microalgae industry is gaining global attention and can be widely utilized in different industrial sectors in the future [232]. Table 9 shows 146 companies or organizations that produce a variety of algae-based products or that sell several species. This information is important to verify the position of the microalgae's in the market worldwide. The mention of government institutions and universities that develop projects in this sector is above the scope of this publication, it is known that they exist in many countries of the world, betting on microalgae as an alternative fuel in the transport sector, as a solution to reduce GHG and to meet future food and feed needs.

The legend of "Uses/applications" column (Table 9) is as follows: (note that not all are applicable for each listed company).

A: CO_2 sequestration from industrial systems;
B: Nutraceuticals and/or food and/or feed (including aquaculture and/or pet foods);
C: Health care and/or pharmaceutical products and/or beauty care (cosmeceuticals);
D: Soils and/or water solutions (fertilizers and/or wastewater treatment and/or water desalination);
E: Biofuels (green crude oil, gasoline, biodiesel, renewable diesel, jet fuel, bio-oil, ethanol, biogas, syngas, methane, among others);
F: Biotechnology applications (algae oil and compounds extraction) and/or equipment's (bioreactors and/or other systems) and/or laboratory analysis;
G: Specific algae (biomass) production and/or algae harvesting/cultivation systems;
H: Bioproducts/biomaterials (bioplastics, biostimulants, natural pigments, among others) production.

Both Table 8 and Table 9, shows that in Europe, Portugal represents one of the countries with the greatest development in the areas of microalgae (including the biorefineries implementation) since the edaphoclimatic conditions help in this process. Portugal is the country in Europe with the highest solar radiation, the main source of raw material for microalgae. Several CO_2 production focus can also be identified that help in the implementation of a microalgae production system through the capture of CO_2 essentially from exhaust gases of several industrial units. At the aquaculture

Table 8
Microalgal biorefineries all over the world [230].

Continent	Country	Company	Technological level	Uses/applications	Website
America	Brazil and United State of America (USA)	Solazyme	Commercial/Flagship	Microalgae production and cosmetics products, bioplastics, oils, encapsulated lubricant and fuels	http://solazymeindustrials.com/
	USA	Algenol	Demo	Personal care ingredients, foods, biofuels (from ethanol to crude oils), biofertilizers and biostimulants	https://www.algenol.com/
		BioProcess Algae, LLC		Microalgae production and other products: feed (including fish), chemicals compost, nutraceuticals, ethanol and biodiesel	http://www.bioprocessalgae.com/
Europe	Denmark	Kalundborg Symbiosis	Demo	Wastewater treated and microalgae production	http://www.symbiosis.dk/en/
	Portugal	A4F Algae for future	Industrial/Demo/Pilot	Bioengineering projects for the industrial microalgae production, biofuels, microalgae-based products and applications	https://a4f.pt/en
		Algafarm (A4F Algae for future) Secil/Allmicroalgae	Commercial/Demo	Microalgae (*Chlorella*) biomass production and others by-products (utilized for biofuels)	https://a4f.pt/en/projects/algafarm
		Buggypower (Portugal), Lda	Demo	Algal biomass for biofuels production and other products (fatty acids, antioxidants, minerals, pigments, vitamins and others)	http://www.buggypower.eu/
	Spain	AlgaEnergy	Pilot	Microalgae production for agriculture, aquaculture, food and feed, natural extracts, cosmetics, gardening and biofuels	https://www.algaenergy.com/
	The Netherlands	TNO-Valorie		Biofuels (biodiesel) and by-products	https://www.tno.nl/media/2818/tno-valorie-flyer-uk.pdf
		AlgaePARC		Develop technologies both on a lab and pilot scale for microalgae production and by-products	http://www.algaeparc.com/

Table 9
Current microalgal producers, uses and applications [233–240].

Continent	Country	Company	Uses/applications								Website
			A	B	C	D	E	F	G	H	
America	Canada	AlgaeCan Biotech Ltd.		✓		✓					https://algaecan.com/
		EBPI-Environmental Bio-Detection Products Inc.						✓			http://www.ebpi-kits.com/
		Symbiotic EnviroTek Inc.	✓	✓		✓	✓				https://symenv.com/
	United State of America (USA)	ABPDU-Advanced Biofuels and Bioproducts Process Development Unit		✓	✓	✓	✓				https://abpdu.lbl.gov/
		Accelergy				✓					http://www.accelergy.com/
		ACEnT Laboratories LLC					✓	✓			http://acentlabs.com/
		Agcore Technologies	✓	✓	✓		✓				http://www.agcoretech.net/index.html
		Algae Floating Systems, Inc.	✓	✓			✓				http://www.algaefloatingsystems.com/
		AlgaBT LLC		✓	✓						https://www.algabt.com/
		Algepower, Inc.		✓		✓		✓			http://algepower.com/
		Algae Systems LLC	✓			✓	✓				http://algaesystems.com/
		Algaewheel						✓			https://algaewheel.com/
		Algenesis								✓	https://www.algenesismaterials.com/
		Algeternal technologies, LLC		✓					✓		https://algeternal.com/
		AlgiKnit Inc.								✓	https://www.algiknit.com/
		BioGreen Synergy		✓	✓		✓				http://www.biogreensynergy.com/index.html
		Cellana Inc.		✓			✓				http://cellana.com/
		Checkerspot, Inc.						✓		✓	https://checkerspot.com/
		CLEARAS Water Recovery, Inc.				✓					https://www.clearaswater.com/
		Culture Biosystems		✓			✓	✓			https://www.culturebiosystems.com/
		Cyanotech Corporation		✓					✓		https://www.cyanotech.com/
		Desert Sweet BioFuels	✓	✓			✓				http://desertsweetbiofuels.com/
		Earthrise Nutritionals, LLC		✓							https://www.earthrise.com/
		ENERGYbits Inc.		✓							https://www.energybits.com/
		Exxon Mobil Corporation					✓				https://corporate.exxonmobil.com/
		Global Algae Innovations, Inc.						✓			http://www.globalgae.com/
		Global Thermostat		✓	✓	✓				✓	https://globalthermostat.com/
		Gross-Wen Technologies				✓	✓			✓	https://algae.com/
		Heliae Development, LLC				✓					https://heliaeglobal.com/
		Manta Biofuel				✓	✓		✓		https://mantabiofuel.com/
America	USA	MicroBio Engineering Inc.		✓		✓	✓	✓			https://microbioengineering.com/
		NCMA Bigelow Laboratory for Ocean Sciences							✓		https://ncma.bigelow.org/cms/index/index/
		OVIVO USA, LLC						✓			https://www.ovivowater.com/
		Phenometrics, Inc.						✓			https://www.phenometricsinc.com/
		Qualitas Health			✓			✓			https://www.qualitas-health.com/
		Raven Engineered Films						✓			https://ravenefd.com/
		Spira, Inc.		✓	✓						https://www.spirainc.com/
		Synthetic Genomics Inc.					✓	✓			https://syntheticgenomics.com/
		Valensa International		✓							https://valensa.com/
		Zivo Bioscience Inc.		✓	✓						https://www.zivobioscience.com/
Asia	Brunei	MC Biotech Sdn. Bhd.		✓					✓		https://mcbiotech.com.bn/
	India	Oilgae	✓			✓	✓	✓			http://www.oilgae.com/
		Parry Nutraceuticals							✓		http://www.parrynutraceuticals.com/
		Prolgae *Spirulina* Supplies Pvt. Ldt.		✓					✓		https://www.prolgae.com/
		SNAP-Natural & Alginate							✓		https://snapalginate.com/
	Indonesia	Neoalgae		✓	✓						https://neoalgae-halal.com/
	Iran	QMAB-Qeshm Microalgae Biorefinery		✓	✓	✓	✓			✓	http://qmabco.com/
	Israel	Algatech			✓			✓			https://www.algatech.com/
		Brevel		✓	✓	✓	✓				https://brevel.co.il/
		UniVerve							✓		https://www.univerve.co.il/
		Yemoja Ltd.						✓			https://yemojaltd.com/
	Japan	Japan Algae Co., Ltd.			✓				✓	✓	http://www.sp100.com/
		Euglena			✓		✓				https://www.euglena.jp/
Europe	Austria	Ecoduna		✓	✓						https://www.ecoduna.com/en/
	Belgium	MicroBioTests				✓					https://www.microbiotests.com/
		Proviron industries							✓		http://www.proviron.com/en
		Tomalgae C.V.B.A		✓							http://www.tomalgae.com/
	Czech Republic	Algamo s.r.o						✓	✓		https://www.algamo.cz/
	Denmark	Ocean Rainforest							✓		http://www.oceanrainforest.com/
	Finland	Redono	✓			✓					https://www.redono.fi/

level, Portugal shelter to the largest variety of microalgae species in the world, specifically at the Algae Collection of the University of Coimbra (UC) with 4000 different strains of microalgae from freshwater in its possession. Considering all these factors, both in terms of biorefineries and in other industrial sectors (mainly food), Portugal has a high potential, that can to be considered in the future such us one of the countries with the greatest evolution and progress in terms of microalgae, whenever the edaphoclimatic conditions don't change significantly with the climate change. The study entitled Evaluation of the Potential of Biomass to Energy in Portugal - Conclusions from the CONVERTE Project demonstrated that there are 29,395 ha with potential for the production of microalgae, these areas being specifically localized in mainland Portugal [241].

Considering again Tables 8 and 9, can be confirmed that with base the wide climatic diversity presented in the USA, this is the country has most invested in the installation, development and implementation of industrial units in the American continent. Some of them are for the production of biofuels (e.g. biodiesel, bioethanol, jet fuel, green crude oil, gasoline, among others) from microalgae, just like in other varieties of products, in order to protect and assure several commercial sectors. Among these are the nutraceuticals, food and feed, fertilizers production, wastewater treatment, CO_2 sequestration, algae oil and compounds extraction, health care, cosmeceuticals and pharmaceutical products, units for the bioreactors production, bioplastics, biostimulants, natural pigments, among others.

Lastly, Table 9 shows that on the Asian continent, the countries that represent the largest investment in the microalgae sector are India and Israel, being once more fundamental the Region's climate, main responsible for the development of microalgae. In India, the only microalgae sectors that are not yet developed are health care, pharmaceutical, beauty care and bioproducts/biomaterials production (including in the Israel case).

It is important to refer that we believe that exist more microalgae industrial installations in several countries, however, the Table 9 represents a large compilation of these industries type around the world.

7. Conclusions

As described in detail along the text, microalgal biotechnology can be widely regarded as a solution to solve humanity's several challenges regarding environmental problems. However, despite the commercialization of microalgae has been a reality in the last decades, still high costs of production have directed final uses, mostly, to high-added-value products and niche markets. Therefore, as highlights of this review, can be concluded:

- The utilization of residues/waste resources opens a window of opportunity that shouldn't be neglected in order to improve the cost-effectiveness and sustainability of the microalgae mass production, especially in what concerns biofuels production;
- The integration of residues/wastes treatment with concomitant microalgae production can address the issues of both energy sustainability and waste recycling in the frame of the circular bioeconomy, lowering microalgal production costs related with bioenergy and biofuel prices and competitiveness;
- Concepts of circular economy (aimed at waste minimization or even elimination) and bioeconomy (in which residues/wastes are used as feedstocks for bio-based products, biomaterials and biofuels, replacing fossil-based feedstocks) must increasingly be considered. Thus, the sustainability issues environmental, social and economic are addressed together;
- Residues/wastes-based biorefineries involving microalgae are expected to fulfill an important part of the increasing demand for energy, fuels, chemicals and materials worldwide, ideally towards de "zero waste discharge" concept;
- Microalgae products may cover a range from low volume and high benefit specialties to high volume and low-cost goods such as biofuels.

This review compiled the modern challenges affecting the planet and how microalgae are expected to solve them. Although the future for microalgae applications derived from waste treatment seems to be promising, a long way still needs to be paved in order to be an important part of the modern industry. More research efforts and investments in different fields of knowledge are required, from the biological, biochemical and engineering perspectives, among others. The proactive collaboration and engagement of different drivers such as technologists, economists, engineers, entrepreneurs and politicians are expected to be crucial to pushing forward microalgae-based businesses towards an increasingly greener society.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the Biomass and Bioenergy Research Infrastructure (BBRI)-LISBOA-01-0145-FEDER-022059, which is supported by Operational Programme for Competitiveness and Internationalization (PORTUGAL 2020), by Lisbon Portugal Regional Operational Programme (Lisboa 2020) and by North Portugal Regional Operational Programme (Norte 2020) under the Portugal 2020 Partnership Agreement, through the European Regional Development Fund (ERDF) .

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Update

Renewable Energy
Volume 167, Issue , April 2021, Page 962–965

DOI: https://doi.org/10.1016/j.renene.2020.12.018

Renewable Energy 167 (2021) 962–965

Contents lists available at ScienceDirect

Renewable Energy

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

Corrigendum to “Microalgae in a global world: new solutions for old problems?” [Renewable Energy volume 165, part 1, (2021) 842–862]

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The authors regret that part of Tables 4 and 9 were not fully published in the original article. In this document we insert the tables in their complete form.

Table 4 (full version). Lipid potential production from microalgae biomass.

Substrate	Reactor	Strains	Light (μmol m^{-2} s^{-1})	Light source	Biomass concentration (g L^{-1})	Biomass production (g L^{-1} d^{-1})	Lipid production (g L^{-1} d^{-1})	Reference
Synthetic culture medium								
Bold's Basal Medium	Flasks	*Chlorella* sp. (UMACC050)	40	Artificial	NR	0.60	0.229	[145]
Synthetic medium (Z)	Flasks	*Chlorella* sp.	≈80[a]	Artificial	0.594	1.44	0.1901	[146]
		Planktothrix isothrix			0.640	0.28	0.0168	
		Synechococcus nidulans			0.401	0.20	0.0272	
Synthetic medium (WC)		*Scenedesmus acuminatus*			0.640	0.42	0.0571	
		Pediastrum tetras			0.528	0.36	0.0623	
		Chlamydomonas sp.			0.536	0.39	0.0834	
		Lagerheimia longiseta			0.460	0.21	0.0239	
		Synechococcus nidulans			0.560	0.69	0.0938	
		Monoraphidium contortum			0.296	0.15	0.0298	
Synthetic medium (C)	Flasks	*Sinechocystis sp.*	≈80[a]	Artificial	1.295	0.39	0.0542	[146]
		Romeria gracilis			0.542	0.22	0.0244	
		Aphanothece sp.			0.458	0.29	0.0299	
Synthetic medium	PBR	*Chlorella minutissima*	NR	Internal light (Blue LED)	0.044–0.0625	0.062	0.0057 –0.0089	[147]
Artificial seawater f/2 medium	Airlift PBR	*Chlorella minutissima 26a*	133	Artificial	NR	0.1886	0.0928	[148]
Synthetic medium BG11	BC-PBR	*Chlorella* sp. FC2 IITG	100-1,700	Natural sunlight	8.6	1.4	0.753	[149]
Wastewater culture medium								
Municipal wastewater (Centrate)	Biocoil	*Chlamydomonas reinhardtii*	220	Artificial	NR	2	0.505	[150]
Municipal wastewater Secondary	Flasks	*Chlorella vulgaris*	≈140	Artificial	1.03	0.1665	0.04138	[151]
					1.11	0.13876	0.04559	

DOI of original article: https://doi.org/10.1016/j.renene.2020.11.014.
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https://doi.org/10.1016/j.renene.2020.12.018

(*continued*)

Substrate	Reactor	Strains	Light (μmol m^{-2} s^{-1})	Light source	Biomass concentration (g L^{-1})	Biomass production (g L^{-1} d^{-1})	Lipid production (g L^{-1} d^{-1})	Reference
Municipal wastewater Secondary (75%) + primary (25%)								
Municipal wastewater	MPBR	*Chlorella vulgaris*	112.3	Artificial	1.84	0.0963	0.02576	[152]
Secondary	(continuous)	*Scenedesmus obliquus*			1.72	0.0888	0.02957	
Sewage	VBCPBR	*Golenkinia* SDEC-16	≈60	Artificial	1.9	0.07089	0.01562	[153]
BG11					2.05	0.07409	0.04343	
Sewage Treatment Plant	Flasks	*Scenedesmus sp.* ISTGA1	≈50	Artificial	1.81	NR	0.452	[154]
Cattle wastewater after previous digestion in a hybrid anaerobic reactor	Airlift PBR (batch)	*Scenedesmus obliquus* (ACOI 204/07)	≈60	Artificial	3.22–3.70	0.358	0.062–0.064	[11]
	Airlift PBR (continuous)				1.92–2.40	0.183	0.017–0.027	
Tertiary Livestock wastewater	SBR	*Botryococcus braunii*	490 (38.75 W m^{-2})	Artificial	≈2.6	0.3156	N.R.	[155]
Piggery biogas slurry	FPCP	Mixed: *Desmodesmus* sp., *Bacillus* and *Pseudomonas*	400	Artificial	NR	0.47	0.07431	[156]
Piggery wastewater	PBR	*Chlorella* sp.	300	Artificial	≈8	0.681	0.155	[157]
	PSBR	*Chlorella vulgaris*	793.5	Natural sunlight	NR	57.87 g m^{-2} d^{-1}	27.25 g m^{-2} d^{-1}	[158]
Algal bloom hydrolysate	Flasks	*Chlorella pyrenoidosa*	200	Artificial	4.36	0.436	0.188	[159]
Dairy	PBR	*Ascochloris* sp.	3,366 −3,978 W m^{-2}	Natural sunlight	2.04	0.292	0.098	[160]
Paper and pulp		*Scenedesmus acuminatus*	240	Artificial	8.22 (max value)	0.685	0.137	[161]
Olive-oil mill	PBR	*Chlorella pyrenoidosa*	359 μE m^{-2} s^{-1}	Artificial	NR	0.03 (1.25 mg L^{-1} h^{-1})	≈0.0103 g L^{-1} d^{-1}	[162]
Meat-processing industry	BC-PBR	*Scenedesmus* sp.	1,797 - 2,101[b]	Natural sunlight	1.169 (max value)	26.5–52.5	1.8–3.7	[12]
		Scenedesmus sp.	1,269 - 2,254[b]	Natural sunlight	0.225–0.371	10.5–12.1	0.3–0.8	

[a] Original article was written in kLux; [b] Original article was written in μE m^{-2} s^{-1}; PBR - Photobioreactor; BC-PBR - Bubble Column Photobioreactor; PSBR - Porous substratum biofilm reactor; SBR - Bench scale sequencing batch reactor; FPCP - Flat-Plate Continuous Photobioreactor; HRP - High rate ponds; MPBR - Membrane Photobioreactor; BCPBR - Vertical bubble-column photo-bioreactor; NR – Not reported.

Table 9 (full version). Current microalgal producers, uses and applications [233–240].

Continent	Country	Company	Uses/applications								Website
			A	B	C	D	E	F	G	H	
America	Canada	AlgaeCan Biotech Ltd.		✓		✓					https://algaecan.com/
		EBPI-Environmental Bio-Detection Products Inc.						✓			http://www.ebpi-kits.com/
		Symbiotic EnviroTek Inc.	✓	✓		✓	✓				https://symenv.com/
	United State of America (USA)	ABPDU-Advanced Biofuels and Bioproducts Process Development Unit		✓	✓	✓	✓				https://abpdu.lbl.gov/
		Accelergy				✓					http://www.accelergy.com/
		ACEnT Laboratories LLC					✓	✓			http://acentlabs.com/
		Agcore Technologies	✓	✓	✓		✓				http://www.agcoretech.net/index.html
		Algae Floating Systems, Inc.	✓	✓			✓				http://www.algaefloatingsystems.com/
		AlgaBT LLC		✓	✓						https://www.algabt.com/
		Algepower, Inc.		✓		✓		✓			http://algepower.com/
		Algae Systems LLC	✓			✓	✓				http://algaesystems.com/
		Algaewheel						✓			https://algaewheel.com/
		Algenesis								✓	https://www.algenesismaterials.com/
		Algeternal technologies, LLC		✓					✓		https://algeternal.com/
		AlgiKnit Inc.								✓	https://www.algiknit.com/
		BioGreen Synergy		✓	✓		✓				http://www.biogreensynergy.com/index.html
		Cellana Inc.		✓			✓				http://cellana.com/
		Checkerspot, Inc.						✓		✓	https://checkerspot.com/
		CLEARAS Water Recovery, Inc.				✓					https://www.claraswater.com/
		Culture Biosystems		✓			✓	✓			https://www.culturebiosystems.com/
		Cyanotech Corporation		✓					✓		https://www.cyanotech.com/
		Desert Sweet BioFuels	✓	✓			✓				http://desertsweetbiofuels.com/
		Earthrise Nutritionals, LLC		✓							https://www.earthrise.com/
		ENERGYbits Inc.		✓							https://www.energybits.com/

(*continued on next page*)

(*continued*)

Continent	Country	Company	Uses/applications A	B	C	D	E	F	G	H	Website
		Exxon Mobil Corporation					✓				https://corporate.exxonmobil.com/
		Global Algae Innovations, Inc.						✓			http://www.globalgae.com/
		Global Thermostat		✓	✓	✓				✓	https://globalthermostat.com/
		Gross-Wen Technologies				✓	✓			✓	https://algae.com/
		Heliae Development, LLC				✓					https://heliaeglobal.com/
		Manta Biofuel				✓	✓		✓		https://mantabiofuel.com/
	USA	MicroBio Engineering Inc.		✓		✓	✓	✓			https://microbioengineering.com/
		NCMA Bigelow Laboratory for Ocean Sciences							✓		https://ncma.bigelow.org/cms/index/index/
		OVIVO USA, LLC						✓			https://www.ovivowater.com/
		Phenometrics, Inc.						✓			https://www.phenometricsinc.com/
		Qualitas Health			✓			✓			https://www.qualitas-health.com/
		Raven Engineered Films						✓			https://ravenefd.com/
		Spira, Inc.		✓	✓						https://www.spirainc.com/
		Synthetic Genomics Inc.					✓	✓			https://syntheticgenomics.com/
		Valensa International		✓							https://valensa.com/
		Zivo Bioscience Inc.		✓	✓						https://www.zivobioscience.com/
Asia	Brunei	MC Biotech Sdn. Bhd.		✓					✓		https://mcbiotech.com.bn/
	India	Oilgae	✓			✓	✓	✓			http://www.oilgae.com/
		Parry Nutraceuticals							✓		http://www.parrynutraceuticals.com/
		Prolgae *Spirulina* Supplies Pvt. Ldt.		✓					✓		https://www.prolgae.com/
		SNAP-Natural & Alginate							✓		https://snapalginate.com/
	Indonesia	Neoalgae		✓	✓						https://neoalgae-halal.com/
	Iran	QMAB-Qeshm Microalgae Biorefinery		✓	✓	✓	✓			✓	http://qmabco.com/
	Israel	Algatech			✓			✓			https://www.algatech.com/
		Brevel		✓	✓	✓	✓				https://brevel.co.il/
		UniVerve							✓		https://www.univerve.co.il/
		Yemoja Ltd.						✓			https://yemojaltd.com/
	Japan	Japan Algae Co., Ltd.			✓				✓	✓	http://www.sp100.com/
		Euglena			✓		✓				https://www.euglena.jp/
Europe	Austria	Ecoduna		✓	✓						https://www.ecoduna.com/en/
	Belgium	MicroBioTests				✓					https://www.microbiotests.com/
		Proviron industries							✓		http://www.proviron.com/en
		Tomalgae C.V.B.A		✓							http://www.tomalgae.com/
	Czech Republic	Algamo s.r.o						✓	✓		https://www.algamo.cz/
	Denmark	Ocean Rainforest							✓		http://www.oceanrainforest.com/
	Finland	Redono	✓			✓					https://www.redono.fi/
	France	Algama		✓							https://www.algamafoods.com/
		AlgoLight		✓	✓						http://www.algolight.com/
		AlgoSource Group		✓							https://algosource.com/en/
		Bioréa SAS		✓	✓			✓	✓		https://www.biorea.fr/en/
		Cyane		✓					✓		https://www.cyane.eu/en/
		Ennesys				✓					http://www.ennesys.com/en/
		Fermentalg		✓	✓						https://www.fermentalg.com/
		Greensea SAS		✓							http://greensea.fr/en/
		Microphyt		✓	✓						http://www.microphyt.eu/en/
		Naturis Pharma SRL							✓		https://www.naturispharma.com/
		Odontella SAS		✓							https://www.odontella.com/fr/home-2/
		Olmix Group		✓	✓						https://www.olmix.com/
		Synoxis Algae						✓			https://www.synoxis-algae.com/
	Germany	Algoliner GmbH & Co. KG						✓			https://www.algoliner.de/home
		Astaxa GmbH							✓		http://www.algae-biotech.com/
		bbe Moldaenke GmbH		✓				✓			https://www.bbe-moldaenke.de/en/
		CellDEG GmbH						✓			https://celldeg.com/features/technology/
		GBEX-Global Biomass Exchange			✓				✓		https://www.gbex.de/en/
		Ludwig Bölkow Campus					✓	✓			https://www.lb-campus.com/
		MIAL GmbH		✓					✓		http://mial.eu/
		Subitec GmbH						✓			https://subitec.com/en
	Iceland	Algalif Iceland ehf.			✓				✓		https://algalif.com/
	Italy	Archimede Ricerche Srl		✓	✓						http://www.archimedericerche.com/
		Biospira Srl		✓					✓		https://www.biospira.it/en/
		F & M Fotosintetica & Microbiologica S.r.l						✓			http://www.femonline.it/
		Severino Becagli SRL		✓	✓				✓		https://www.severinobecagli.it/en/
		Tolo Green SRL		✓	✓						https://www.tologreen.it/en/
	Norway	MicroA			✓			✓	✓		https://microa.no/
	Portugal	$Alga_2O$, Lda.							✓		https://alga2o.pt/index.php/pt/
		Algae Tagus - Produção de Microalgas	✓								https://algatec.eu/en/production/
		Allmicroalgae-Natural Products		✓	✓						http://www.allmicroalgae.com/
		Aqualgae SL	✓	✓	✓	✓					http://aqualgae.com/en/home/
		Bluemater				✓					https://www.bluemater.com/
		Biotrend - Inovação e Engenharia em Biotecnologia							✓		http://www.biotrend.pt/
		Lusalgae		✓	✓						http://lusalgae.pt/
		Madebiotech						✓			https://www.madebiotech.com/
		Naturextracts							✓		https://naturextracts.com/

(*continued*)

Continent	Country	Company	Uses/applications								Website
			A	B	C	D	E	F	G	H	
		Nutrally Algae Solutions SL							✓		https://www.nutrally.net/es
		Pagarete Microalgae Solutions		✓					✓		https://www.pagaretems.com/
		Phytoalgae		✓							http://phytoalgae.pt/
		PhytoBloom (Necton)		✓	✓		✓	✓			http://www.necton.pt/
		Spirulina da Serra - Monchique		✓					✓		https://spirulina-da-serra.com/
		Spirulina Portugal		✓					✓		https://www.spirulinaportugal.com/
		Stellarialga	✓			✓					https://www.stellarialga.com/
		Tomar Natural		✓					✓		https://tomarnatural.pt/
		5essentia spirulina azores		✓					✓		https://5essentia.com/
	Slovenia	AlgEn D.o.o	✓	✓	✓	✓	✓				https://algen.eu/
	Spain	AgriAlgae®								✓	https://www.agrialgae.es/?lang=en
		Algalimento SL							✓		http://www.algalimento.com/
		Algasol		✓	✓	✓	✓			✓	http://algasolrenewables.com/
		Algatek			✓			✓			http://algatek.co.uk/
		Biorizon Biotech				✓			✓		http://www.biorizon.es/?lang=en
		Fitoplancton Marino, S.L		✓	✓						http://www.fitoplanctonmarino.com/
		Monzón Biotech		✓	✓				✓		https://mznbiotech.com/
		Neoalgae Micro Seaweeds Products SL		✓	✓				✓		http://neoalgae.es/
	Sweden	Alfa Laval Corporate AB					✓				https://www.alfalaval.com/
		AstaReal AB			✓	✓					http://www.astareal.se/
		Simris Alg AB		✓	✓				✓		https://simrisalg.se/en/
	Switzerland	Algorigin		✓	✓				✓		https://algorigin.com/en/
		Bühler AG		✓							https://www.buhlergroup.com/
	The Netherlands	AlgaSpring B.V.		✓					✓		https://www.algaspring.nl/
		CaribAlgae	✓			✓	✓	✓			https://www.caribalgae.com/
		Corbion		✓	✓			✓			https://www.corbion.com/
		Evodos B.V.						✓	✓		https://www.evodos.eu/
		FeyeCon		✓	✓			✓			http://www.feyecon.com/
		Hi, I'm Algae		✓	✓	✓					https://hiimalgae.com/nl
		LGem						✓			https://lgem.nl/
		Liqoflu Ltd.				✓			✓		http://liqoflux.com/
		Omega Green		✓	✓	✓	✓			✓	https://www.omegagreen.nl/
	Turkey	Akuamaks		✓							https://www.akuamaks.com/en/
	United Kingdom (UK)	Algaceuticals		✓	✓			✓			https://www.algaceuticals.com/
		Algaplex						✓			http://algaplex.co.uk/
		Algenuity		✓	✓						https://www.algenuity.com/
		EnAlgae					✓	✓	✓		http://www.enalgae.eu/
		Firglas Ltd.		✓							http://firglas.com/
		Kilbride Biotech Group Ltd						✓			http://kbbiotech.com/
		Membranology						✓			https://membranology.com/
		SuSeWi						✓			https://www.susewi.life/
		Varicon Aqua Solutions Ltd		✓				✓			http://www.variconaqua.com/
		Xanthella						✓			http://www.xanthella.co.uk/
Oceania	Australia	Csiro		✓	✓		✓			✓	https://www.csiro.au/
		Future of Algae for Food & Feed (FAFF)		✓							https://www.futureofalgae.org/
		Nonfood		✓					✓		https://eatnonfood.com/
		sbr Saalbio Refinaries		✓			✓				https://www.saalbio.com/
		Techverse, Inc.						✓			http://techverseinc.com/

The authors would like to apologise for any inconvenience caused.