Scoping the potential for outdoor microalgae production in the Azores

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Microalgae cultivation has received much attention due to some desirable characteristics such as fast growth rates, high photosynthetic efficiencies and the production of valuable biochemicals. Mass cultivation of microalgae for commercial purposes is already a reality in some locations being an activity with approximately 45 years. The Azores archipelago, located in the North Atlantic Ocean off the coast of Portugal, features a temperate climate. To evaluate the feasibility of local outdoor microalgae production, certain fundamental factors must be analysed. In this study water, light, temperature, carbon sources, nutrients, international outlook and regional context were analyzed from the perspective of a local outdoor commercial microalgae production. A SWOT analysis was applied to the analysed factors to evaluate the strengths, weaknesses, opportunities and threats. The results nominate the Azores as a promising location to implement an outdoor production of value-added products from microalgae.

Key words: Microalgae, Azores archipelago, outdoor commercial production, SWOT analysis

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INTRODUCTION

Microalgae are photosynthetic micro-organisms, living in saltwater, brackish or freshwater environments that convert sunlight, water, nutrient and carbon dioxide to biomass (Ozkurt 2009). They exist as individual cells, colonies or chains of cells but do not form differentiated, multicellular organisms, as do macroalgae (Bahadar & Khan 2013). Their rapid growth, high biomass yields, metabolite diversity, and ease of harvest from open ponds or closed photobioreactor systems give them excellent commercial potential as sustainable environmentally-friendly resources (Gao et al. 2012).

Microalgal use by indigenous populations has occurred for a long time. Indeed, edible blue-green algae (Cyanobacteria) including *Nostoc*, *Arthrospira* (*Spirulina*) and *Aphanizomenon* species have been used as food for thousands of years (Jensen et al. 2001). In a short period of about 40 years, the microalgal biotechnology industry has grown and diversified significantly (Spolaore et al. 2006). Nowadays, the microalgal biomass market produces about 5,000 t of dry matter/year and generates a turnover of approximately US$ 1.25×10^9/year. These rates relate only to biomass as a commercial product. Thus the total global production of microalgal biomass, including processed products, would be rated between 8,000 and 10,000 t (Pulz & Gross 2004; Posten & Walter 2012; Vigani et al. 2015).

The most important parameters regulating algal growth are quantity and quality of nutrients, light, temperature, pH, turbulence and salinity. The various parameters may be interdependent and differently tolerated by each species (Barsanti & Gualtieri 2014).

The Azores archipelago is formed by nine volcanic islands located in the North Atlantic Ocean where the American, Eurasian, and African plates meet at a triple junction (Searle 1980). The climate is mainly classified as temperate with no dry season and a mild summer; however, Santa Maria and Graciosa islands are better classified as temperate with dry and warm summers. The average annual temperature range is low and there are numerous local microclimates, derived from the mountainous nature of the islands (Cropper 2013). There is a considerable amount of fresh water bodies but the microalgae species that inhabit them have been subject of few ecological studies (e.g. Barrois 1886; Bourrelly & Manguin 1946; Gonçalves 2008).

The present study describes the international and regional context for outdoor microalgae production and uses a SWOT analysis to analyse the potential of the Azores in this area.

NATURAL FACTORS

WATER

Given that microalgae cultivation is carried out in liquid medium, water is a primary factor of the process. Water consumption has been postulated to be a resource barrier for large-scale production of microalgae (Batan et al. 2013). The amount of water needed for the production of 1 Kg of microalgae biomass in closed systems can be estimated from final biomass concentration values. Using the final concentrations given by Yang et al. 2012 of 0.5 g/L to 7.56 g/L, and assuming no water loss, the production of 1 Kg of biomass consumes between 2,000 and 132 L of water. To these values must be added the water needed for the remainder of the process. Borowitzka & Moheimani (2013) reported that due to evaporation rates in regions of high solar irradiation, it is highly unlikely that open pond culture of freshwater microalgae can be used to produce biofuels and the focus for this purpose must be on species able to grow in saltwater, preferably over an extended salinity range.

By using seawater or wastewater, the freshwater usage can be reduced by as much as 90%. Nevertheless, a significant amount of freshwater must still be used for culture no matter whether sea/wastewater serves as the culture medium or how much harvested water is recycled (Yang et al. 2010). However, if algae are grown in an enclosed system such as a photobioreactor, the use of freshwater is feasible as the water lost by evaporation can be recovered and recycled (Borowitzka & Moheimani 2013).

The oceanic position of the Azores gives it virtually unlimited access to saltwater. The Azorean climate is further characterized by regular and abundant rainfall, thermal mildness, and high air humidity. The annual average rainfall ranges from 749 mm in Santa Maria to 1,512 mm in Flores, with an annual average of 1,033 mm for the region. According to Cropper (2013), rainfall varies significantly throughout the year being December the rainiest month and July the driest (Table 1). The high volume of water derived from rainwater could be used as feedstock for the production of microalgae. On the other hand, the existence of days on which rainfall exceeds 100 mm could cause problems in open pond systems.

According to SRAM (2012), the Azores have an annual water need for human activities of 195.2 x 10^6 m^3 (Table 2). The balance between availability and demand is 2,089.5 x 10^6 m^3. In all islands the supply greatly exceeds the demand, with emphasis to Pico which presents a supply 449 times greater than the demand. São Miguel presents the highest water demand (165.4 x 10^6 m^3) due to higher population and activities, yet only 34.26% of the available water is consumed annually (SRAM 2012). In terms of superficial and subterranean water availability of either fresh or saltwater, all islands are therefore compatible with the commercial production of microalgae.

Table 1. Average monthly and annual precipitation (mm) from five islands of the Azores: Santa Maria (SMA), São Miguel (SMG), Terceira (TER), Flores (FLR) and Faial (FAI) (Cropper 2013).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Vila do Porto, SMA	75	76	65	57	45	50	22	34	59	71	88	106	749
Ponta Delgada, SMG	79	76	82	69	53	32	23	42	79	87	99	109	829
Lajes, TER	116	136	116	75	61	51	49	57	97	128	139	159	1,184
Santa Cruz, FLR	170	146	134	99	97	88	49	72	118	159	168	211	1,512
Horta, FAI	87	91	82	58	64	53	30	50	78	96	100	102	891
Average	105	105	96	72	64	55	35	51	86	108	119	137	1,033

Table 2. Total water requirements, water availability and water balance for the islands of the Azores (hm^3) (SRAM 2012).

		S. Maria	S. Miguel	Terceira	Faial	Graciosa	Pico	São Jorge	Flores	Corvo	Total
Total water requirements		0.5	165.4	8.8	1.9	0.5	1.7	1.2	15.1	0.1	195.2
Water availability	Super-ficial	19.3	261.1	146.6	55.2	6.2	181	103.5	71.5	10.5	854.8
	Sub-terranean	15.1	221.8	193.1	74.1	15	582	219	101.4	8.3	1,429.8
	Total	34.4	482.9	339.7	129.3	21.2	763	322.5	172.9	18.8	2,284.6
Balance		33.9	317.5	330.9	127.4	20.7	761.3	321.3	157.8	18.7	2,089.5

LIGHT

Light is the driving force of photosynthesis, as well as a major issue in cell photo-acclimatization. Both photoperiod and light intensity have a significant effect on microalgal growth. Khoeyi et al. (2012) showed that at different light intensities, an increase in light duration was associated with increased specific growth rates in *C. vulgaris*. Of the various intensities and photoperiods tested, the maximum biomass (2.05 ± 0.1 g L^{-1}) was recorded at an intensity of 62.5 µmol photons m^{-2} s^{-1} and 16:8 h. A study of *Tetraselmis chui* (Chlorophyta) by Meseck et al. (2005) suggested that in photoperiods less than 12 h, cell quota, nutrient-uptake and division rate are energy limited, regardless of light intensity.

The number of daylight hours in the Azores varies from 9.3 in December to 14.7 in June. According to Azevedo (2015), three months have more than 14 daylight hours (Fig. 1). Algal growth is compromised when the number of hours of light falls below 12 (Meseck et al. 2005). This means that a reduction in production of outdoor cultivation is expected in the Azores between October and February.

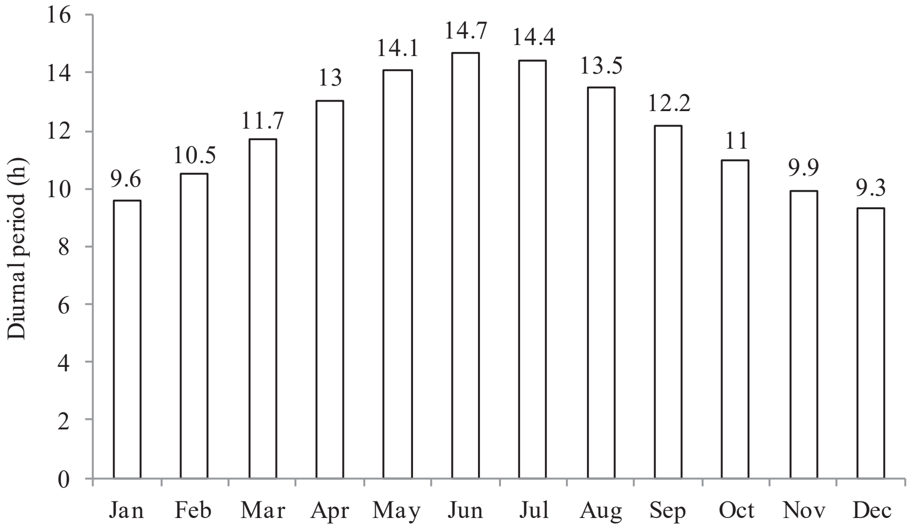

Fig. 1. Diurnal period throughout the year in the Azores (after Azevedo 2015).

However, above a certain threshold, light intensity becomes an inhibiting factor. This photoinhibition phenomenon will generally cause reversible damage to the photosynthetic process (Rubio et al. 2003). Since outdoor microalgal cultures are exposed to environmental conditions, limiting and even inhibiting values for photosynthesis are likely to be recorded on clear days (Carvalho et al. 2011). According to Vonshak et al. (1989), e.g., *Spirulina platensis* (Cyanobacteria) becomes "light saturated" well below one quarter of full sunlight and maximum growth rate measured was only at about 20 µmol photons m^{-2} s^{-1}.

Defining the optimal light intensity for the growth of microalgae is complex since it depends on several factors, e.g. species, cultivation system and culture density. Khoeyi et al. (2012) recorded the maximum biomass at a light intensity of 62.5 µmol photons m^{-2} s^{-1} for a 16:8 h light/dark photoperiod duration in *Chlorella vulgaris* (Chlorophyta). The results of Kitaya et al. (2005) demonstrated that the highest multiplication rate of the microalga *Euglena gracilis* (Euglenophyta) was at a light flux of about 100 µ mol m^{-2} s^{-1} with continuous lighting. Chen et al (2011), observed a reduction in productivity with light intensity above 260 µmol photons m^{-2} s^{-1} in *Chlorella* sp. Mata et al. (2012) reported the highest biomass production in *Tetradesmus obliquus* (formerly *Scenedesmus obliquus*) (Chorophyta) at the light intensity of 165 µmol photons m^{-2} s^{-1}.

The amount of energy from solar radiation in the Azores is around 42 MJ m^{-2} day^{-1} at Summer solstice, decreasing to 15 MJ m^{-2} day^{-1} at Winter solstice. However, given the radiation attenuation along its path through the atmosphere, in particular due to the typical cloudiness of the region, these values are significantly higher than those observed on the surface of the islands. The highest annual average values of surface radiation energy are observed in Santa Maria (14.4 MJ m^{-2} day^{-1}) and Flores (12.8 MJ m^{-2} day^{-1}) (Azevedo 2015, Table 3). The variation through the year is nevertheless high: December has an average radiation of 6 MJ m^{-2} day^{-1}, whereas in July this value reaches 21 MJ m^{-2} day^{-1}.

The conversion of Einstein, a unit defined as the energy in one mole (6.022×10^{23}) of photons to J is not an easy task because energy is inversely proportional to wavelength, and therefore the unit is frequency dependent. In order to do so, several assumptions should be introduced. In terms of energy, sunlight at Earth's surface is around 52 to 55% infrared (above 700 nm), 42 to 43% visible

(400 to 700 nm), and 3 to 5% ultraviolet (below 380 nm).

The photosynthetically active radiation (PAR) corresponding to photon wavelength range from 380 nm and 700 nm is assumed to contain 42.5% of the total solar energy impinging the earth surface. It is assumed that average visible photons (550 nm) have an energy content of 217.503 kJ/mol.

Thus, 1 E of visible light (PAR) is assumed to correspond to 217.5 KJ of PAR energy and 511.8 KJ of total radiation. This means that 1 µmol photon $m^{-2}s^{-1}$ can be considered equivalent to 0.0187 MJ m^{-2} d^{-1}.

Table 3. Average monthly and annual global solar radiation on the surface (MJ m^{-2} day^{-1}), for five islands of the Azores: Santa Maria (SMA), São Miguel (SMG), Terceira (TER), Flores (FLR) and Faial (FAI) (Azevedo 2015).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Horta, FAI	6.7	8.7	12.1	16.1	19	19.2	21.6	20.5	15.4	11.2	7.5	5.9	13.7
Santa Cruz, FLR	6.1	7.9	11.6	15	18.2	18.6	20.3	19.3	14.3	9.9	6.6	5.3	12.8
Vila do Porto, SMA	7.1	9.2	12.9	16.4	20.9	20.3	22.4	21	16.1	11.7	8	6.7	14.4
Lajes, TER	7	9.1	12.7	16.3	19.7	19.7	21.5	20.4	16.2	11.4	7.6	6	14.0
Ponta Delgada, SMG	7	9.1	12.2	15.6	18.7	18.7	20.5	19.4	15.4	11.3	7.8	6.4	13.5
AVG	6.8	8.8	12.3	15.9	19.3	19.3	21.3	20.1	15.5	11.1	7.5	6.1	

TEMPERATURE

Temperature is a crucial factor for outdoor production of microalgae. The effect of elevated temperatures is often described as more deleterious than low temperatures (Ras et al. 2013). Although the optimum temperature is species and strains-specific, most microalgae are capable of carrying out photosynthesis and cellular division over a range of temperatures between 15 and 30 °C, with optimal conditions between 20 and 25 °C (Li 1980). Kim et al. (2012) demonstrated that optimum temperature conditions for growth of *Chlorella* and *Dunaliella* (Chlorophyta) strains were 25 and 27 °C, respectively. According to Converti et al. (2009), *C. vulgaris* growth appeared to be negatively affected at temperatures above 30 °C. At 35 °C this microalga exhibited in fact a 17% decrease in its growth rate when compared to 30 °C. Further increase in temperature (38 °C) led to an abrupt interruption of microalgal growth, and eventually to cell death. Microalgae are also sensitive to temperature changes, thus maintaining constant temperature is important for stable long-term cultivation (Kim et al. 2012).

The Azores have a low annual thermal range: the annual mean temperature varies from 17.3 °C in Ponta Delgada to 17.9 °C in Vila do Porto and Horta (Cropper 2013). The monthly mean temperature varies from 14 °C in February and 23 °C in August (Table 4).

The mean temperature decreases steadily at a rate of 0.9 °C per 100 m in altitude, until the dew point temperature is reached, at a height on average close to 400 m. From there, the temperature decreases less abruptly, at the rate of 0.6 °C per 100 m (SRAM 2012). This effect must be taken into consideration when planning the location of a microalgae plant.

Table 4. Average monthly and annual mean temperature (°C) from five islands of the Azores: Santa Maria (SMA), São Miguel (SMG), Terceira (TER), Flores (FLR) and Faial (FAI) (Cropper 2013).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	ANN
Santa Maria, SMA	15	14	15	16	17	19	22	23	22	20	17	16	18
Ponta Delgada, SMG	14	14	14	15	16	19	21	22	21	19	17	15	17
Lajes, TER	14	14	14	15	17	19	21	22	21	19	17	15	17
Santa Cruz, FLR	15	14	15	16	17	19	22	23	22	19	17	15	18
Horta, FAI	15	15	15	16	17	19	22	23	22	20	17	16	18
Average	15	14	15	15	17	19	21	23	22	19	17	16	

The low thermal amplitudes of the Azores are a positive factor for outdoor cultivation of microalgae, given their sensitivity to temperature fluctuations. The absence of natural temperature extremes, coupled with the greenhouse effect in photobioreactors means that a culture temperature within the 15 to 30 °C range, considered adequate for most species (Ras et al. 2013), can be maintained throughout the year in the Azores without the need for heating or cooling the culture.

The ability for microalgae to grow under high temperatures is species dependent. The existence of thermophilic species explains optimal growth temperatures above 40 °C (Ras et al. 2013), whereas thermophilic cyanobacteria (formerly blue-green alga) are reported to have optimal growth temperatures covering the entire range from 30 °C to over 65 °C (Castenholz 1981). Some studies have investigated the use of high temperature-tolerant species for carbon dioxide sequestration (Ono & Cuello 2006), metal bioremoval (Radway et al. 2001), and bioactive compound production (Fish & Codd 1994) among others. The use of geothermal waters for temperature control in commercial microalgae cultivation has previously been studied with positive results (Bedell 1985; Fournadzhieva et al. 2002). Geothermal energy proved to be a significant factor for economic efficiency of microalgal cultivation given the opportunity to heat the cultures in the cooler seasons.

The present-day volcanic activity in the Azores is due to the interaction between the complex tectonic setting and the presence of a mantle melting anomaly. It is characterized not only by seismic activity, but also by several secondary manifestations of volcanism such as high temperature fumaroles (95-100 °C), steaming ground, thermal springs, cold CO_2 rich springs and soil diffuse degassing areas (Viveiros et al. 2012). Currently on the island of São Miguel there are two geothermal energy plants, responsible for the production of 40% of the electricity consumption on the island, and a third plant is projected for Terceira (EDA 2014). Hot water is a by-product of geothermal activity and could be used for the production of thermophilic microalgae. In addition, natural fumarolic fields such as those of Furnas and Ribeira Grande, where water temperatures up to 100 °C are recorded, may also enable this type of production.

CARBON SOURCES

Carbon is an essential factor for microalgal growth (Borowitzka & Moheimani 2013). Microalgal biomass contains approximately 50% carbon by dry weight (Mirón et al. 2003), all of which is typically derived from carbon dioxide. Producing 100 t of algal biomass fixes roughly 183 t of carbon dioxide (Chisti 2007). Microalgae can fix CO_2 from different sources: the atmosphere, industrial flue gases, and soluble carbonates ($NaHCO_3/Na_2CO_3$) (Elumalai et al. 2014). Generally, atmosphere CO_2 is the carbon source for open pond culturing of microalgae. As the carbon dioxide content in atmospheric air is relatively low (approximately 400 ppm, Blunden & Arndt 2014), cell growth is limited and can be slow (Borowitzka & Moheimani 2013).However, several studies have shown tolerance of microalgae to elevated CO_2 concentrations (Negoro et al. 1991; Maeda et al. 1995; Chiu et al. 2011). Westerhoff et al. (2010) reported that *Scenedesmus* sp. and *Chlorella* sp. (Chlorophyta) grew well and tolerated exposure to a gas mixture containing up to 20% CO_2 applied continuously in batch reactors. This property has led to the use of microalgae to sequester industrial carbon dioxide while producing valuable biomaterials.

Exhaust gases from thermal power stations typically contain 10-20% CO_2, corresponding to an increment of 250–500 times relatively to atmospheric air. In the Azores the industry responsible for the majority of CO_2 emissions is Electricidade dos Açores, S.A. (EDA), through thermo-electric production. In 2013, EDA was responsible for emitting 398,976 tons of CO_2 (Table 5). This CO_2 source could be used for the production of microalgae, reducing production costs and simultaneously minimizing environmental impacts. In São Miguel there are also two geothermal power plants in operation. Although geothermal energy is generally considered a benign energy source to the environment, it releases a considerable amount of CO_2 to the atmosphere (Suryata et al. 2010). These authors demonstrated that geothermal flue gas can be efficiently used as a feedstock for microalgae cultivation, a concept that could be used for microalgal production in the Azores.

Table 5. Total energy production (MWh) and CO_2 emissions (t) for the Azores in 2013 (EDA 2014).

	Energy production	**CO_2 emissions**
Santa Maria	21,074	23,307
São Miguel	412,183	128,706
Terceira	208,854	121,281
Graciosa	13,552	17,213
São Jorge	29,254	33,789
Pico	45,608	27,953
Faial	49,047	31,572
Flores	11,452	13,129
Corvo	1,442	2,025
Total	792,466	398,975

CO_2 is also produced by soil emissions. Present-day volcanic activity in the Azores is marked by highly active fumarolic fields, hot springs and diffuse soil degassing phenomena (Ferreira et al. 2005). These authors identified degassing areas associated with hydrothermal systems of active central volcanoes in São Miguel, Terceira and Graciosa islands. Less significant degassing fields exist in Faial, Pico, São Jorge and Flores islands while there are no reported gas emanations in Santa Maria or Corvo islands (Ferreira 1994; Viveiros 2003). In certain areas of Furnas village soil temperatures can be as high as 100 °C and soil gas concentrations of CO_2 reaches between 50 and 100%. Data from the last 15 years demonstrate the stability of these soil CO_2 emissions. A rough estimation for the CO_2 naturally emitted from an area of approximately 6.2 km^2 is 1,100 t d^{-1} (Viveiros 2010). The idea of associating the production of microalgae to this natural phenomenon of CO_2 release and temperature would be an innovative use.

NUTRIENTS

Various culture media have been developed and used for isolation and cultivation of freshwater algae and are useful for growing a wide variety of algae (e.g. Guillard 1975; Becker 1994). The growth medium for microalgae production must provide the inorganic elements that constitute the algal cell. Main elements include nitrogen, phosphorus, iron and in some cases silicon. Nutrients such as phosphorus must be supplied in significant excess because of its reduced bioavailability (Chisti 2007). In commercial cultivation of microalgae, the culture medium represents a significant cost (Mata et al. 2010). In order to reduce production costs and increase commercial viability, many studies have proposed the use of costless nutrients with environmental advantages.

Many species of microalgae, for instance, are able to effectively grow in wastewater utilizing its abundant organic carbon and inorganic N and P (Pittman et al. 2011). Urban effluents tertiary treatment involves the removal of nitrogen and phosphorus prior to discharge into the environment. Usually, the removal of phosphorus is done chemically, which adds to the cost of treatment. The capacity of microalgae to simultaneously consume nitrogen and phosphorous could play an important role in the tertiary treatment of municipal wastewaters. The generated biomass could then be used for biofuels, feed/food proteins and chemicals (Rawat et al. 2011; Arbib et al. 2013). Park et al. (2011) suggested the use of high rate algal ponds (HRAPs) for wastewater treatment, establishing that they produce a much smaller environmental footprint compared to commercial algal production which consumes freshwater and fertilizers. In the Azores, there are municipal wastewater treatment plants in the islands of São Miguel, Santa Maria, Terceira, Graciosa, and Corvo but only one of them performs tertiary treatment. Producing microalgae using this facility would be an environmental friendly activity.

Other important source of nutrients is agricultural wastewater, which is often derived from manure, and can be very high in N and P content (Borowitzka & Moheimani 2013). Agriculture is an important sector of the economic structure of the Azores in which livestock production, in particular the dairy industry, play a major role. In 2013 there were a total of 44,500 cows for milk production while the meat sector slaughtered 125,834 animals and exported live 17,866 (Table 6).

Table 6. Total animals slaughtered locally and exported in 2013 in the Azores (SRRN 2013).

		Nº Animals	Weight (t)
Slaughtered locally	Cattle	60,479	13,152
	Swine	65,355	4,906
	Poultry	-	4,724
Exported	Cattle	17,866	4,525
Total		143,700	27,307

Other interesting nutrient source is the whey effluent from the cheese industry, which represents about 85% of the total milk used in the process (Parmjit & Kennedy 2012). In 2013 (SRRN 2014), 565 million L of milk were delivered to local factories in the Azores, resulting in the production of 28 thousand tons of cheese. Millions of liters of whey have no current application and impose an economic and environmental burden. Recent studies have demonstrated the feasibility of using whey as culture media for microalgae production (Girard et al. 2014; Espinosa-Gonzalez et al. 2014).

All the above mentioned sources could be used for microalgae production in the Azores, as demonstrated by An et al. (2003), who grew *Botryococcus braunii* (Chlorophyta) using piggery wastewater and Johnson & Wen (2010) who utilized dairy manure for the production of *Chlorella* sp. However, this would only be possible in areas of intensive farming such as cattle (Wang et al. 2010), swine (Godos et al. 2010) and poultry (Singh et al. 2011) or close to cheese factories.

SOCIAL AND ECONOMIC FACTORS

INTERNATIONAL OUTLOOK

Although many major technical challenges remain before microalgal biofuels become a commercial reality (Greenwell et al. 2009), nowadays microalgae are used as a source for several products of commercial interest, namely intracellular molecules such as proteins, including essential amino acids, high molecular weight polysaccharides, pigments, lipids, polyunsaturated fatty acids (PUFAs), biological active molecules and the biomass itself (Posten & Walter 2012). The global production of microalgal biomass is rated between 8,000 and 10,000 tones, generating a turnover of approximately US$ 1.25×10^9/year (Pulz & Gross 2004).

According to Borowitzka (2013) several high-value microalgae products are already well established, and there are clear opportunities for additional new products. With the presently greatly increased efforts to commercialize microalgae, new products are likely to be developed and marketed in the next decade. Currently only a few species of microalgae producing high value products (e.g. *Spirulina* spp. - Cyanobacteria, *Dunaliella salina*, *Chlorella* spp. - Chlorophyta) are grown commercially in open ponds in Australia, China, India, Israel, Japan, Thailand, and the USA (Boruff et al. 2015). Western Australia hosts the largest commercial microalgae cultivation plant in the world, the *Dunaliella salina* (Chlorophyta) plant producing the valuable beta-carotene. The plant is located in Hutt Lagoon, on the central coast of Western Australia, and comprises a total pond area of over 740 ha (Borowitzka 2013).

According to the previously described, microalgae production is a growing business with potential opportunities. The global interest in the biotechnology of microalgae has been followed in Europe. Microalgae have been widely recognized as a key value chain for the bioeconomy. The European SET-PLAN (strategic energy technological plan) recognizes microalgae of strategic importance for biomaterials production (Gouveia et al. 2015). In addition, past and current European R&D projects also evidence the importance of microalgae biotechnology.

REGIONAL CONTEXT

The Azores have the human capital and the political will to take advantage of opportunities in the field of microalgae production. The University of the Azores (UAc) is a higher education institution with centers on three islands. The education offer covers a range of courses related to biotechnology such as biology, engineering, or pharmaceutical sciences. Research areas of the UAc include biochemistry, aquaculture and algal biology. A pilot project of microalgae cultivation in partnership with a startup company (ALGICEL) gave positive results which are now being consolidated. One of the general conclusions was that it is possible and promising to produce *H. pluvialis* (Chlorophyta) in the Azores (Xavier 2011).

The Azores Government promotes a number of investment incentives that aim to promote the sustainable development of the regional economy, including research-based innovation. In fact, biotechnology and aquaculture are among the strategic priorities set out in the research and innovation strategy for smart specialisation of the region (SPI AÇORES 2014).

DISCUSSION AND CONCLUSIONS

A SWOT analysis of the main factors required for microalgae cultivation in the Azores was performed and shows a set of strengths that favour intensive outdoor culture in the Azores (Table 7).

Some of the local natural conditions favour the development of commercial microalgae production, given that they surpass many of the basic requirements of this activity. Apart from the natural conditions, the activities already present in the region may also be considered strengths. The major limitation identified in the present study is related to the relatively unfavourable local characteristics regarding solar light intensity. Nevertheless, this does not preclude the production of microalgae, and can be overcome by working at lower culture densities, or using photobioreactors with smaller diameters, to increase light penetration (Richmond 2004). The threats identified, commercial competition coupled with increased costs from geographic isolation, may be surpassed by the listed opportunities. In fact, the Strategy for Research and Innovation for Intelligent Specialisation of the Azores (SPI AÇORES 2014) places a strategic priority on biotechnology for the period 2014-2020. The EU structural funds could therefore leverage the opportunities for companies interested in investing in this area. To focus on high-value compounds would increase the commercial viability of a local microalgae production by reducing the percentage of the cost of taking the products to the market. Some of the local characteristics mentioned, such as precipitation and annual average sunshine, suggest that closed production systems (photobio-reactores) are more suitable. The availability of technology, infrastructures, academic and professional skills were also identified as strengths.

All the above suggests that the Azores have conditions to implement outdoor production of value-added products from microalgae, providing end-users relevant benefits from an alternative economic resource. However, in order to facilitate future investment in the region, identifying the most suitable locations for microalgae cultivation is imperative. The present work gives several indications in this direction but further social and economic concerns should be addressed, such as the availability of land and the affordability of property.

Table 7. SWOT analysis of the factors that potentiate microalgae cultivation in the Azores.

Strengths	Weaknesses	
High freshwater and saltwater availability Low thermal range/absence of temperature extremes Annual mean temperature allows production throughout the year CO_2 available from natural and industrial sources Availability of high temperature geothermal water Availability of nutrients from urban and agriculture wastewaters Human capital available Presence of research infrastructures	Low solar radiation Photoperiod below 12h on 4 months	**Internal Factors**
Opportunities	**Threats**	
Microalgae cultivation is a growing business worldwide Regional financing programs supporting research and innovation in general, including biotechnology and aquaculture	Competition with other areas Increased costs from geographic isolation	**External Factors**
Positive	**Negative**	

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