



Life cycle assessment of the production of the red antioxidant carotenoid astaxanthin by microalgae: from lab to pilot scale



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ABSTRACT

The freshwater green microalga *Haematococcus pluvialis* is the richest source of natural astaxanthin. Astaxanthin is a high-value red carotenoid pigment commonly used in the food, feed and cosmetics industries due to its well-known antioxidant, anti-inflammatory and antitumour properties. This study assesses the environmental impacts associated with the production of natural astaxanthin from *H. pluvialis* at both lab and pilot scale. Closed airlift photobioreactors with artificial illumination, typically used for the production of high-value products to avoid contamination risks and allow controlled lighting conditions, were considered. The study extends from the production of the different inputs to the system to microalgal production, harvesting and further extraction of the carotenoid. The life cycle assessment was performed following the ISO 14040 and ten impact categories were considered in the study: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidant formation.

According to the results, electricity requirements represented the major contributor to the environmental burdens among the activities involved in the production of astaxanthin. For the lab-scale process, the air supply and the production of chemicals and lab materials were also significant contributors in several categories. In the pilot-scale production, the relative environmental impacts were greatly reduced, partially due to changes implemented in the system as a result of lab-scale environmental assessment. However, the production of electricity still dominated the impacts in all categories, particularly due to the cultivation stage. For this reason, a sensitivity assessment was proposed in order to identify alternative photobioreactor configurations for astaxanthin production. Two of the evaluated options, based on the use of sunlight instead of artificial illumination, presented significant reductions of impact. However, the improvements observed in these cases were limited by the decrease in biomass productivity associated with sunlight culture systems. Therefore, a two flat-panel photobioreactor system with artificial illumination is proposed as a suitable option, allowing reductions between 62% and 79% of the impact depending on the considered category.

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1. Introduction

Microalgae are considered as a potential feedstock for the production of a wide diversity of compounds, ranging from value added products such as foodstuffs, chemicals, pharmaceuticals and nutraceuticals to next-generation biodiesel (Olaizola, 2003; Li et al., 2007; Sheehan et al., 1998). These organisms are the primary

producers of organic matter in aquatic environments due to their photosynthetic activities (Suh et al., 2006). Under changing environmental conditions (e.g. nutrient deprivation, light limitation), microalgae can become stressed, causing them to overproduce some compounds of interest such as carotenoids (Aflalo et al., 2007; García-Malea et al., 2009; Shahid et al., 2013). As cell factories for the production of high-value biomolecules, microalgae present numerous advantages such as i) the availability of cultivation on non-arable land; ii) the possibility of using wastewaters that provide the nutrients required for growth and, iii) the availability to modify the biochemical composition of the algal cells by varying

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the growth conditions (Stephenson et al., 2010). Even more, one of the most important and potential benefits of these organisms is the possibility of sequestering CO₂ from streams derived from industrial processes (Munir et al., 2012; Olaizola, 2003).

Concerning the mechanisms used for microalgal cultivation, particular interest lies in the development of different cultivation technologies to improve productivity and yield (Brentner et al., 2011; Olaizola, 2003; Stephenson et al., 2010). In general, the cultivation systems can be classified in two main groups: i) open raceway ponds (ORPs) and ii) closed photobioreactors (PBRs). Important differences exist between both configurations: ORPs present higher losses by evaporation, larger requirements of water, higher risks of contamination, lower volumetric productivity, poor mixing and reduced temperature control in comparison with the PBRs. In contrast, they are less energy-intensive and are associated with lower levels of greenhouse gas (GHG) emissions (Brentner et al., 2011; Jorquera et al., 2010). With regard to PBRs, they are closed systems with higher biomass yield but they are more expensive to build and operate than ORPs (Brentner et al., 2011; Jorquera et al., 2010; Stephenson et al., 2010).

Once the microalgae culture is grown, it is harvested. Depending on the product to be recovered, the next step typically entails reducing the water content of the microalgal biomass since low water content enhances the recovery of lipid soluble components and carotenoids (Brentner et al., 2011; Lardon et al., 2009). Different methods can be considered for this purpose: flocculation and settling, centrifugation, filtration or air flotation. The selection of the harvesting method will depend on factors such as energy requirement as well as microalgae cell characteristics: size and density (Brentner et al., 2011; Olaizola, 2003).

Finally, after harvesting, the compounds of interest are extracted by different methods. Commonly, organic solvents such as hexane or methanol (Kobayashi and Sakamoto, 1999; Stephenson et al., 2010) as well as supercritical fluids (Brentner et al., 2011) are used for extraction. Enzymatic extraction, still under development, could be a very interesting alternative to be established in the future specifically if the final product is intended for human consumption (Mercer and Armenta, 2011).

The freshwater green microalga *Haematococcus pluvialis* is the richest source of natural astaxanthin, a carotenoid (or pigment) commonly found in marine animals and traditionally used as a pigmentation source for fish aquaculture (Fábregas et al., 2001; García-Malea et al., 2005; Hata et al., 2001). Astaxanthin (3,3'-dihydroxy- β , β -carotene-4,4'-dione; C₄₀H₅₂O₄) is a high-value red carotenoid, which starts accumulating in the lipid vesicles of *H. pluvialis* during the transition between green vegetative cells and red aplanospores after exposure to stress conditions (Aflalo et al., 2007; Fábregas et al., 2001). However, astaxanthin production can be hampered by the low cell growth rate, the sensitivity of the cells to hydrodynamic stress and changes in cell morphology under various environmental conditions (Hata et al., 2001). Due to its excellent antioxidant properties, astaxanthin has numerous applications; from its use as an additive in food and feed industries, nutraceuticals to cosmetics market (Koller et al., 2012). Recently, its anti-inflammatory and anti-cancer activities confirmed its importance in the medical sector (Aflalo et al., 2007; Guerin et al., 2003).

Many established large scale facilities produce natural astaxanthin from *H. pluvialis* (Algatechnologies Ltd.; BioReal AB; Cyanotech Corp.) despite the competition with the cheaper synthetic astaxanthin from petrochemical sources that dominates 95% of the current astaxanthin world market, estimated at US\$250 million (Guerin et al., 2003; Lorenz and Cysewski, 2000; Murray et al., 2013; Olaizola, 2003). Consumer growing demand for natural products makes synthetic routes less desirable (Herrero et al., 2006; Lorenz and Cysewski, 2000), which justifies the considerable

effort that is being paid on the promotion of biotechnological alternatives with environmental friendly production systems (Olaizola, 2003; Rodríguez-Sáiz et al., 2010). It is expected that in a short time, the production costs of the natural production process should be more competitive with synthetic astaxanthin after the optimisation of the production technology. In this sense, Li et al. (2011) have estimated a production cost of \$718/kg natural astaxanthin in a conceptually designed plant of 900 kg astaxanthin per year, which is significantly lower to \$1000/kg synthetic astaxanthin from companies such as DSM, BASF and NHU.

Furthermore, synthetic astaxanthin consists of a racemic mixture with a stereoisomeric ratio of 1:2:1 for the 3R,3'R/meso/3S,3'S isomers, whereas natural astaxanthin mainly corresponds to 3S,3'S isomer (Wang et al., 2008). This difference influences several properties related to the biological function of astaxanthin, such as the antioxidant potential or the shelf life, which makes natural astaxanthin more valuable than the synthetic alternative in nutraceutical and pharmaceutical markets, reaching prices up to \$100,000 kg⁻¹ (Chen et al., 2007; Chew and Park, 2006; Olaizola, 2003; Spolaore et al., 2006).

Life Cycle Assessment (LCA) is a standardised methodology for addressing all the environmental concerns derived from the production process of a product by evaluating the potential environmental impacts associated with its whole life cycle chain (ISO 14040, 2006). To date, LCA has been usually applied to the evaluation of the environmental performance of algae-based biodiesel production (Brentner et al., 2011; Campbell et al., 2011; Clarens et al., 2010) and cofiring microalgae with coal (Kadam, 2002). Most of these studies were performed by extrapolation of lab- and pilot-scale conditions due to the absence of data on biodiesel production from microalgae at industrial scale (Lardon et al., 2009). Although several LCA studies related to biotechnological processes as well as to the production of biologically active molecules have been already published (Jegannathan and Nielsen, 2013; Pietrzykowski et al., 2013), there are not available studies focused on the production of these biocompounds by microalgae. Therefore, to the best of our knowledge, this paper presents for the first time a detailed life cycle inventory and quantification of the related impacts of the production of high-value natural astaxanthin from *H. pluvialis* using a photobioreactor with artificial illumination. The results highlight the most important environmental issues where future developments should pay special attention.

2. Materials and methods

2.1. Goal and scope definition

Similarly to previous works (Pietrzykowski et al., 2013), this study aims to perform a comparative assessment of the environmental impacts associated with the production of *H. pluvialis* astaxanthin for nutraceutical or pharmaceutical uses at both lab and pilot scale in airlift photobioreactors with artificial illumination. This dual approach will allow evaluating the differences between both perspectives, considering the influence of scale-up as well as the effectiveness of the changes introduced in the real pilot process after the lab-scale experiments. In a first stage, the environmental impacts associated with the operation of a 15 L tubular airlift photobioreactor were evaluated. In this case, astaxanthin was obtained as a pure compound after a conventional solvent extraction. The lab experiments regarding the cultivation of the microalga were carried out by the Bioengineering Group of the Earth and Life Institute at the University of Louvain (Belgium) while the extraction processes were developed by the Shannon Applied Biotechnology Centre at the Limerick Institute of Technology (Ireland).

Subsequently, a pilot-scale process was developed by the biotechnological company Algae Health (Ireland). This process used the information obtained from the laboratory system as a basis for the scale-up to a pilot process operated in two stages which was performed in consecutive 1000 L airlift photobioreactors. The target product from the pilot process was a nutraceutical oleoresin with a content of 10% astaxanthin.

In both stages, the study extends from the production of the different inputs to the system, to the cleaning of the reactor, the preparation of the culture medium, as well as microalgal cultivation, harvesting and final extraction of the carotenoid as a pure compound.

2.1.1. Lab-scale process

As mentioned, the main purpose of this study was to analyse the environmental effect of scale-up from laboratory to pilot-scale process for the production of *Haematococcus* astaxanthin extract from microalgae cultivated in photobioreactors. Lab-scale production in one step was considered initially in order to identify the main stages of the system and the most relevant hot spots that may also affect the pilot process.

The LCA study started with the selection of the functional unit, to which all inputs and outputs to the system are referred. For the lab-scale production, the functional unit chosen was 1 g of astaxanthin, equivalent to 1 batch of production.

The system for the production of astaxanthin from *H. pluvialis* was divided into five stages, which are described below: i) Cleaning of the reactor, ii) Preparation of the culture medium, iii) Cultivation of the microalga, iv) Harvesting and v) Extraction of the astaxanthin. Fig. 1 shows the different stages and processes that were included in the system boundaries.

i) Cleaning of the reactor

At lab-scale, the use of bleaching agents was considered to clean the reactor. For this purpose, 20 g of sodium hypochlorite, as well as 50 L of tap water and 30 L of sterile autoclaved water were required.

ii) Preparation of the culture medium

The culture medium comprised deionised water containing 0.75 g/L NaNO₃, 0.025 g/L CaCl₂·2H₂O, 0.075 mM MgSO₄·7H₂O, 0.025 g/L NaCl, 0.075 g/L K₂HPO₄·3H₂O, 0.175 g/L KH₂PO₄, 0.0012 g/L vitamin B1, 0.00001 g/L vitamin B12 and trace metals (less than 0.005 g/L). This stage required the addition of nutrients in the specified amounts to deionised water, followed by the sterilisation of the culture medium in an autoclave, as well as the addition of the initial inoculum in 150 mL culture flasks under a sterile flow hood. Volumes of 1.5 L of inoculum and 13.5 L of culture medium were required for the start-up of the photobioreactor.

iii) Cultivation

Firstly, 150 mL cell cultures were statically incubated in flasks at 20 °C and 20 μmol photons·m⁻² s⁻¹ of light intensity from four fluorescent lights (15 W). Cells were subcultured and fresh medium was added in order to increase the cell culture density from 0.3 dry weight (g_{DW})·L⁻¹ to 2 g_{DW}·L⁻¹. Once the required density was reached, the inoculum was added to the prepared medium in the photobioreactor.

The lab-scale photobioreactor consisted of a polyvinyl chloride (PVC) tubular airlift photobioreactor with a volume of 15 L. The reactor was illuminated by six fluorescent bulbs of 36 W and aerated by 1.5 L min⁻¹ of compressed air enriched with 0.5% CO₂ in the feed gas. In this case, 30 g of dried biomass were produced in one batch after 14 days of operation in a single stage, with an astaxanthin content of 4%.

iv) Harvesting

The biomass produced was initially harvested by centrifugation with an efficiency of 95%. A volume reduction of 97% was obtained, with final moisture of 94%. The resulting biomass was kept in a freezer before being freeze-dried to 2% moisture.

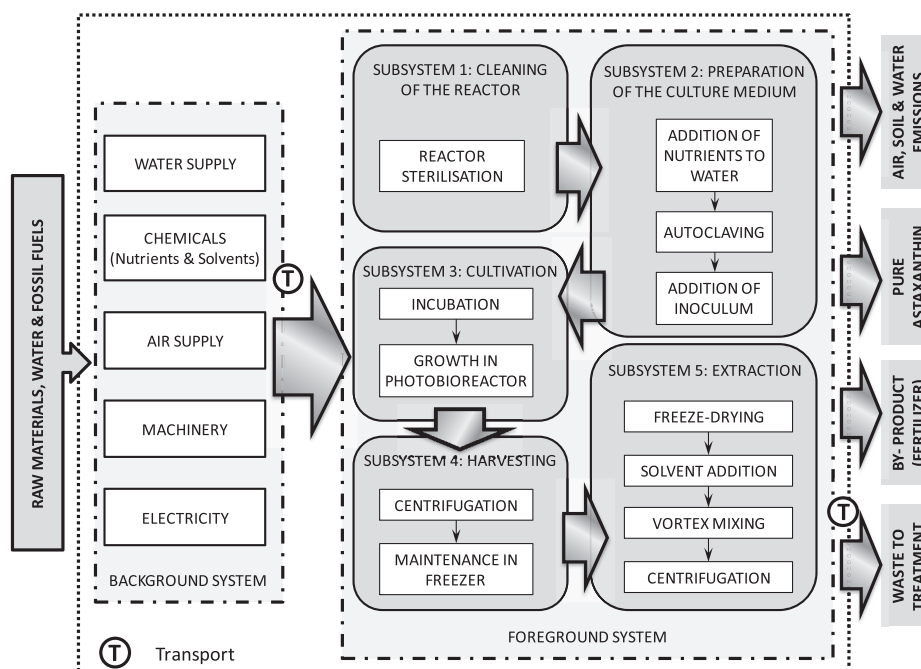


Fig. 1. System boundaries and process chain of the lab-scale case study: production of astaxanthin from *Haematococcus pluvialis* in a 15 L tubular airlift photobioreactor.

v) Extraction

The lab-scale separation process consisted of a conventional solvent extraction with dimethyl sulfoxide (DMSO). After DMSO addition, the mixture was heated to 55 °C and vortexed before separating the pigment phase by centrifugation. Finally, 1 g astaxanthin was obtained with a purity of 95%. As in the case of other marine organisms (Spångberg et al., 2013), the algal residue was considered as a fertiliser due to its content in nitrogen and phosphorous. However, it is important to remark here that this residue contained high-value added components with antioxidant and antimicrobial activities that may have more specialised potential applications.

2.1.2. Pilot-scale process

After the optimisation of operational parameters, a two-stage pilot system was designed. The process consisted of a first growth stage with nutrient excess followed by a second stress stage limited in phosphate and nitrate. In both stages, the excess culture medium was recirculated, so at least five cultures could be performed with the water initially added. Therefore, the selected functional unit was 800 g of astaxanthin, corresponding to a complete cycle of five cultures.

In order to obtain applicable conclusions from the lab-scale study, the pilot system was divided into the same five stages as the lab production of *Haematococcus* astaxanthin, as shown in Fig. 2. The deviations from the original lab process are detailed below.

i) Cleaning of the reactor

In the case of the pilot process, two options were evaluated for the cleaning and sterilisation stage. Firstly, the use of bleaching agents was considered. Another possibility was assessed, consisting of the circulation of ozonised water through the reactor for a 4-h

period, which seems to be a more appropriate option for a commercial scale production.

ii) Preparation of the culture medium

The culture medium for the pilot process was prepared with river and rain water, previously purified by reverse osmosis and UV filter to remove undesired salts and microorganisms. As the cultivation was carried out in two stages, namely growth and stress stage, two cultivation mediums were prepared. In the medium for the growth stage, the added nutrients were 0.875 g/L NaNO₃, 0.1975 g/L K₂HPO₄, 0.0875 g/L KH₂PO₄, 0.0305 g/L CaCl₂ g/L, 0.141 g/L MgSO₄, 0.0125 g/L NaCl, 0.004 g/L citric acid, 0.05 g/L Na₂CO₃, 0.00275 g/L disodium ethylenediaminetetraacetate (EDTA), 0.00143 g/L H₃BO₃ and trace elements (less than 0.001 g/L). The culture medium used for the stress stage was equivalent to the previous one, except for the absence of K₂HPO₄ and KH₂PO₄, as well as for the concentration of NaNO₃, which was reduced to 0.0875 g/L.

iii) Cultivation

In the first stage, the microalga was grown for 8 days in a 1000 L airlift photobioreactor with an excess of nutrients. The reactor was internally illuminated with a 16:8 regime (600 W) and continuously aerated (50 W, 24 h). Afterwards, 50% of the cell culture was taken to an analogous reactor and microalgal cells were allowed to settle, enabling the drainage of 96% of the water, that could be recirculated to the original tank. In the second tank, a stress medium with limiting phosphate and nitrate nutrients was added, inducing astaxanthin accumulation. This stressing cycle required 1200 W for the illumination, as well as 50 W for the agitation motor and 50 W for the aeration pump at a continuous rate during 8 days. At the end of the period, the microalga had turned red and accumulated 4–5% astaxanthin. After settling of the culture broth, approximately 80% water was recovered and recirculated. The

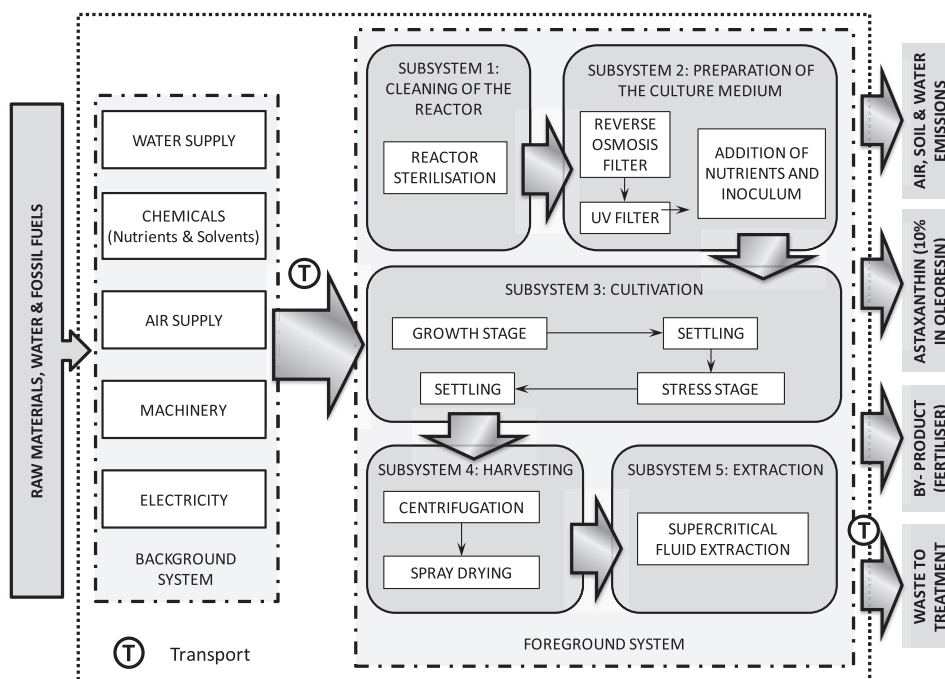


Fig. 2. System boundaries and process chain of the pilot-scale case study: production of astaxanthin from *Haematococcus pluvialis* in a two-stage process with 1000 L internally illuminated airlift photobioreactors in series.

remaining 20% water was then poured off and sent to harvesting stage.

iv) Harvesting

As in the lab-scale process, the biomass was harvested by centrifugation with approximately 95% efficiency. However, in this case a settling step was carried out before centrifugation to preconcentrate the biomass. Therefore, the starting moisture for the centrifugation was lower than that of the lab-scale process, and consequently a lower moisture of 80% was obtained in the pilot process. After spray drying the algal paste, the moisture content was reduced to 5%.

v) Extraction

The lab-scale separation process consisted of a conventional extraction with DMSO. However, this method is not suitable for the production of astaxanthin used in food or pharmaceutical industries due to the DMSO residue (Ni et al., 2007). Therefore, a supercritical CO₂ extraction was chosen to isolate astaxanthin from the algal paste obtained in the pilot-scale process. To do so, the cells were mixed with a dispersing and drying agent prior extraction. Both fish and vegetable oils could be used as a co-solvent. In this case, fish waste oil was employed, in a ratio of 25% weight of sample.

Although the final product of the pilot process is an oleoresin with 10% astaxanthin, the final processing was excluded from the system boundaries to make the results comparable to those of lab-scale process. Thus, the production of pure astaxanthin (95%) was assessed as the final product, and the algal residue was considered as a fertiliser.

2.2. Inventory analysis, data quality and simplifications

The Life Cycle Inventory (LCI) data for the foreground system (i.e. chemicals and electricity consumptions as well as transport distances) consisted of average data obtained by on-site measurements. Concerning water emissions, they were calculated assuming that the nutrients supplied in the culture medium which are not consumed during the algae growth, are directly discharged to water. An identical assumption was made for air emissions.

Concerning the background system, the corresponding inventory data for the production of all the inputs to the system were taken from Ecoinvent database, except from metal components, that were taken from IDEMAT (2001). These inputs include the production of the different chemicals required for the preparation of the culture medium, the electricity used in the different production stages, the distribution of inputs up to the lab gate, lab ware supplies and equipment (flasks, photobioreactor, fluorescent tubes, electronic devices) and waste disposal. A detailed description of the corresponding database reports considered is shown in Table 1. For the equipments, different life spans were considered, according to manufacturers' specifications. An average transport distance of 800 and 600 km within continental Europe was considered for chemicals and materials, respectively, with an average sea distance of 1400 km from the continental Europe to Ireland in the pilot-scale process. Waste transport distance was estimated around 50 km. Disposal in sanitary landfill was considered for all plastic waste, whereas steel components and lamps were sent to either inert landfills or specific waste treatment. Incineration was considered for the filter membrane (polyamide).

With regard to NaNO₃ production, this process is not defined in the Ecoinvent database. Therefore, the considered inventory data correspond to the synthetic process described in UNIDO/IFDC (1998). The method, developed by GIAP, consists of an oxidation

Table 1
Summary of data sources.

Energy	Electricity (Belgian electricity profile) Electricity (Irish electricity profile)	Ecoinvent database (Dones et al., 2007)
Chemicals	NaNO ₃ ^a CaCl ₂ MgSO ₄ NaCl K ₂ HPO ₄ KH ₂ PO ₄ C ₁₂ H ₁₇ ClN ₄ OS · HCl C ₆₃ H ₈₈ CoN ₁₄ O ₁₄ P C ₁₀ H ₁₆ N ₂ O ₈ FeCl ₃ MnCl ₂ ZnCl ₂ CoCl ₂ Na ₂ MoO ₄ C ₆ H ₈ O ₇ C ₆ H ₅ + _{4y} Fe _x N _y O ₇ H ₃ BO ₃ ZnSO ₄ CuSO ₄ Co(NO ₃) ₂ CO ₂ C ₂ H ₆ OS (DMSO) NaClO Deionised water Tap water Na ₂ CO ₃	Ecoinvent database (Althaus et al., 2007)
Air supply	Compressed air Carbon dioxide	Ecoinvent database (Sutter, 2007) Ecoinvent database (Steiner and Frischknecht, 2007) Ecoinvent database (Althaus et al., 2007)
Materials	PVC Polystyrene High density polyethylene Polyethylene terephthalate Gro-lux fluorescent tubes (36 W) Stainless steel Galvanised steel	Ecoinvent database (Hischier et al., 2007) IDEMAT (2001)
Transport	Truck 3.5–7.5 t, Euro 4 Freight ship	Ecoinvent database (Spielmann et al., 2007)
Waste treatment	Sanitary landfill	Ecoinvent database (Doka, 2007)

^a Synthetic route – UNIDO/IFDC (1998) and Oak Ridge National Laboratory (1994).

of ammonia in the presence of platinum catalyst followed by the absorption of the nitrogen oxides produced in an aqueous solution of sodium carbonate and the separation of sodium nitrate and sodium nitrite. Finally, nitric acid is added to convert sodium nitrite to sodium nitrate. Sodium nitrate is separated from the solution and dried in a rotary dryer. Inventory data for the raw materials were taken from Ecoinvent database, whereas energy requirements from Bhat et al. (1994) were considered.

Fish oil, required for the supercritical extraction stage in the pilot-scale process, is not available in the Ecoinvent database. Fish oil is a by-product of fisheries, obtained from the discarded fraction of marine fish such as mackerel, salmon, tuna and cod (Lin and Li, 2009). In this case, the inventory data from Iribarren et al. (2012) were considered.

In this study, no allocation procedure was required since algae cultivation was only focused on astaxanthin production. Therefore, all the environmental burdens were allocated to the amount of astaxanthin produced. The separated biomass residue was considered as a potential fertiliser and the corresponding contents in

Table 2Global inventory for the lab-scale production of astaxanthin from *Haematococcus pluvialis* in a 15 L tubular airlift photobioreactor (functional unit: 1 g astaxanthin).

Inputs from technosphere			
<i>Materials</i>		<i>Materials</i>	
Cleaning of the reactor		Extraction	
Deionised water	28.27 L	Dimethyl sulfoxide (DMSO)	2.63 L
Tap water	47.11 L	Stainless steel	0.31 g
Sodium hypochlorite (NaClO)	18.84 g	Cast metal	0.94 g
Stainless steel	4.70 g	Galvanised steel	8.16 g
Preparation of the culture medium		Anodised aluminium	0.22 g
Deionised water	14.13 L	Polycarbonate	211.05 g
NaNO ₃	10.571 g	<i>Energy</i>	
CaCl ₂ ·2H ₂ O	0.352 g	Cleaning of the reactor	
MgSO ₄ ·7H ₂ O	1.057 g	Autoclaving	1.11 kWh
NaCl	0.352 g	Preparation of the culture medium	
K ₂ HPO ₄ ·3H ₂ O	1.057 g	Autoclaving	0.78 kWh
KH ₂ PO ₄	2.466 g	Addition of inoculum in laminar flow hood	0.19 kWh
C ₁₂ H ₁₇ ClN ₄ OS·HCl	0.0169 g	Cultivation	
C ₆₃ H ₈₈ CoN ₁₄ O ₁₄ P	0.0001 g	Incubation (excluding lights)	40.70 kWh
C ₁₀ H ₁₄ N ₂ Na ₂ O ₈ ·2H ₂ O	0.0634 g	Lighting in incubation stage	9.50 kWh
FeCl ₃	0.0049 g	Lighting in the photobioreactor	68.38 kWh
MnCl ₂	0.0035 g	Air blowing	3.73 kWh
ZnCl ₂	0.0004 g	Harvesting	
CoCl ₂ ·6H ₂ O	0.0002 g	Centrifugation	10.99 kWh
Na ₂ MoO ₄ ·2H ₂ O	0.0003 g	Freezer	5.65 kWh
Stainless steel	26.14 g	Freeze-drying	2.26 kWh
Polystyrene (PS)	3.37 kg	Extraction	
High density polyethylene (HDPE)	124.37 g	Heating of the solvent	0.39 kWh
Polyethylene terephthalate (PET)	0.96 g	Vortex mixing	0.05 kWh
Cultivation		Centrifugation	1.28 kWh
Compressed air (enriched 0.5% CO ₂)	67.91 kg	<i>Transport</i>	
Fluorescent lamps (15 W)	3.04 g	Truck, 3.5–7.5 t, Euro 4 (Chemicals)	2.344 tkm
Polyurethane foam	34.26 g	Truck, 3.5–7.5 t, Euro 4 (Materials)	3.134 tkm
Galvanised steel	79.94 g	Truck, 3.5–7.5 t, Euro 4 (Waste)	0.261 tkm
Gro-lux fluorescent tubes (36 W)	16.15 g		
Polyvinyl chloride (PVC)	40.47 g		
Harvesting			
Distilled water	4.71 L		
Polypropylene (PP)	819.72 g		
Galvanised steel	32.96 g		
Anodised aluminium	0.85 g		
Polycarbonate	422.11 g		
Polyurethane foam	3.00 g		
Stainless steel	20.70 g		
Inputs from environment			
<i>Materials</i>			
Biomass	0.424 g		
Outputs to technosphere		Outputs to environment	
<i>Product</i>		<i>Air emissions</i>	
<i>Haematococcus</i> astaxanthin	1 g	Air (excluding CO ₂)	67.39 kg
Avoided product ^a		CO ₂	0.48 kg
Nitrogen-rich fertiliser	0.573 g	<i>Water emissions</i>	
Phosphorous-rich fertiliser	0.375 g	Water effluent	94.22 L
<i>Waste treatment</i>		NaClO	18.84 g
Steel, to inert landfill	173.847 g	NaNO ₃	0.4770 g
Polystyrene, to sanitary landfill	3.373 kg	CaCl ₂ ·2H ₂ O	0.0159 g
Polyethylene, to sanitary landfill	124.371 g	MgSO ₄ ·7H ₂ O	0.0477 g
Polyethylene terephthalate	0.964 g	NaCl	0.0159 g
Fluorescent lamps, to specific treatment for electronics wastes	19.185 g	K ₂ HPO ₄ ·3H ₂ O	0.0477 g
		KH ₂ PO ₄	0.1113 g
Polyurethane foam, to specific waste treatment	37.26 g	C ₁₂ H ₁₇ ClN ₄ OS·HCl	0.0008 g
Polyvinyl chloride, to sanitary landfill	40.469 g	C ₆₃ H ₈₈ CoN ₁₄ O ₁₄ P	0.00001 g
Polypropylene, to sanitary landfill	819.718 g	C ₁₀ H ₁₄ N ₂ Na ₂ O ₈ ·2H ₂ O	0.0029 g
Aluminium, to sanitary landfill	1.067 g	FeCl ₃	0.0002 g
Polycarbonate, to sanitary landfill	633.162 g	MnCl ₂	0.0002 g
		ZnCl ₂	0.00002 g
		CoCl ₂ ·6H ₂ O	0.00001 g
		Na ₂ MoO ₄ ·2H ₂ O	0.00002 g
		DMSO	6316.6316 L

^a N and P fertiliser dosage is equivalent to 27.266 g of residual biomass.

nitrogen and phosphorous were calculated according to Mulbry et al. (2005). Thus, a nitrogen content of 7% in algal biomass was considered, with 30% of total nitrogen as plant available nitrogen. Regarding phosphorous, it was assumed a content of 1% present in

biomass, with 60% as plant available phosphorus. Once the fertiliser potential was estimated, the equivalent amount of a typical fertiliser (ammonium sulphate as N source and diammonium phosphate as P source) was considered in the model as avoided product, which

Table 3
Global inventory for the production of astaxanthin from *Haematococcus pluvialis* in a two-stage process with 1000 L stirred-tank photobioreactors in series (functional unit: 800 g carotenoid).

Inputs from technosphere			
<i>Materials</i>		<i>Materials</i>	
Cleaning of the reactor		Extraction	
OPTION 1		Drying agent (pelletised diatomaceous earth)	35.46 kg
Tap water	4.009 m ³	Co-solvent (fish/vegetable oil)	4.67 kg
NaClO	4.009 kg	Stainless steel	0.55 kg
OPTION 2		<i>Energy</i>	
Stainless steel	0.200 kg	Cleaning of the reactor (OPTION 2)	
Preparation of the culture medium		Reactor sterilisation with ozonised water	0.12 kWh
NaNO ₃	4.4651 kg	Preparation of the culture medium	
K ₂ HPO ₄	0.9121 kg	Reverse osmosis filtration	7.71 kWh
KH ₂ PO ₄	0.4041 kg	UV filtration	0.35 kWh
CaCl ₂	0.2914 kg	Cultivation	
MgSO ₄	1.3473 kg	Lighting in the photobioreactor	1539.43 kWh
NaCl	0.1194 kg	Air blowing	96.21 kWh
C ₆ H ₈ O ₇	0.0287 kg	Agitation	96.21 kWh
C ₆ H _{5+4y} Fe _x N _y O ₇	0.0287 kg	Harvesting	
Na ₂ CO ₃	0.4778 kg	Centrifugation	1.50 kWh
C ₁₀ H ₁₆ N ₂ O ₈	0.0263 kg	Spray drying	82.70 kWh
H ₃ BO ₃	0.0137 kg	Extraction	
ZnSO ₄	0.0011 kg	Supercritical CO ₂ extraction	158.25 kWh
CuSO ₄	0.0004 kg	<i>Transport</i>	
Co(NO ₃) ₂	0.0002 kg	OPTION 1	
FeCl ₃	0.0028 kg	Truck, 3.5–7.5 t, Euro 4 (Chemicals)	41.87 tkm
ZnCl ₂	0.0001 kg	Truck, 3.5–7.5 t, Euro 4 (Materials)	8.03 tkm
CoCl ₂	0.0001 kg	Truck, 3.5–7.5 t, Euro 4 (Waste)	2.44 tkm
MnCl ₂	0.0098 kg	Ship (Chemicals)	73.27 tkm
Na ₂ MoO ₄	0.0012 kg	Ship (Materials)	18.73 tkm
Stainless steel	0.3446 kg	OPTION 2	
Polyvinyl chloride (PVC)	0.0213 kg	Truck, 3.5–7.5 t, Euro 4 (Chemicals)	38.60 tkm
UV lamps	0.0175 kg	Truck, 3.5–7.5 t, Euro 4 (Materials)	8.15 tkm
Polyamide	0.1169 kg	Truck, 3.5–7.5 t, Euro 4 (Waste)	2.45 tkm
Cultivation		Ship (Chemicals)	67.55 tkm
Stainless steel	8.36 kg	Ship (Materials)	19.01 tkm
Reactor lamps	0.13 kg		
Harvesting			
Stainless steel	3.84 kg		
Inputs from environment			
<i>Materials</i>		<i>Materials</i>	
Biomass	0.017 kg	Air (excluding CO ₂)	434.72 t
River/rain water	2.786 m ³	CO ₂	0.26 t
Outputs to technosphere		Outputs to environment	
<i>Product</i>		<i>Water emissions</i>	
<i>Haematococcus astaxanthin</i>	800 g	NaNO ₃	0.0891 kg
Avoided product ^a		K ₂ HPO ₄	0.0194 kg
Nitrogen-rich fertiliser	0.431 kg	KH ₂ PO ₄	0.0086 kg
Phosphorous-rich fertiliser	0.282 kg	CaCl ₂	0.0041 kg
<i>Waste treatment</i>		MgSO ₄	0.0189 kg
Steel, to inert landfill (OPTION 1)	13.09 kg	NaCl	0.0017 kg
Steel, to inert landfill (OPTION 2)	13.29 kg	C ₆ H ₈ O ₇	0.0004 kg
Polyvinyl chloride, to sanitary landfill	0.02 kg	C ₆ H _{5+4y} Fe _x N _y O ₇	0.0004 kg
Fluorescent lamps, to specific treatment for electronics wastes	0.15 kg	Na ₂ CO ₃	0.0067 kg
		C ₁₀ H ₁₆ N ₂ O ₈	0.0004 kg
		H ₃ BO ₃	0.0002 kg
Textiles, to municipal incineration	0.12 kg	ZnSO ₄	0.00001 kg
Diatomaceous earth, to inert landfill	35.46 kg	CuSO ₄	0.000005 kg
		Co(NO ₃) ₂	0.000003 kg
		FeCl ₃	0.000039 kg
		ZnCl ₂	0.000002 kg
		CoCl ₂	0.000001 kg
		MnCl ₂	0.000138 kg
		Na ₂ MoO ₄	0.000016 kg
<i>Outputs to environment</i>		OPTION 1	
<i>Air emissions</i>		Water effluent	6.79 m ³
Air (excluding CO ₂)	434.72 t	NaClO	4.009 kg
CO ₂	0.24 t	OPTION 2	
		Water effluent	2.79 m ³

^a N and P fertiliser dosage is equivalent to 20.505 kg of residual biomass.

Table 4

Impact assessment results (characterisation step) associated with the lab-scale production of 1 g of *Haematococcus astaxanthin*.

Impact category	Unit	Value
ADP	kg Sb _{eq}	0.716
AP	kg SO _{2eq}	0.447
EP	kg PO ₄ ³⁻ _{eq}	0.157
GWP	kg CO _{2eq}	87.2
ODP	g CFC-11 _{eq}	0.005
HTP	kg 1,4-DB _{eq}	48.6
FEP	kg 1,4-DB _{eq}	33.8
MEP	kg 1,4-DB _{eq}	20.2
TEP	g 1,4-DB _{eq}	4.72
POFP	g C ₂ H _{4eq}	15.4

resulted in negative impacts that were subtracted from the environmental burdens.

The global inventories of lab- and pilot-scale processes are shown in Tables 2 and 3.

2.3. Life cycle impact assessment

Regarding the steps defined within the life cycle impact assessment, classification and characterisation stages were undertaken here (ISO 14040, 2006). Normalisation and weighting were not conducted as these optional (and, to some extent, subjective) elements were not considered to provide additional, robust information for the objectives established in this study. The characterisation factors reported by the Centre of Environmental Science of Leiden University (CML 2001 method) were used (Guinée et al., 2001). The impact potentials (or impact categories) evaluated according to the CML method were: abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), ozone layer depletion (ODP), human toxicity (HTP), freshwater aquatic ecotoxicity (FEP), marine aquatic ecotoxicity (MEP), terrestrial ecotoxicity (TEP) and photochemical oxidants formation (POFP). The software SimaPro 7.3 was used for the computational implementation of the inventories (Goedkoop et al., 2008).

3. Results and discussion

3.1. Lab-scale environmental profile

The characterisation results of the astaxanthin production process are shown in Table 4 for the complete production process

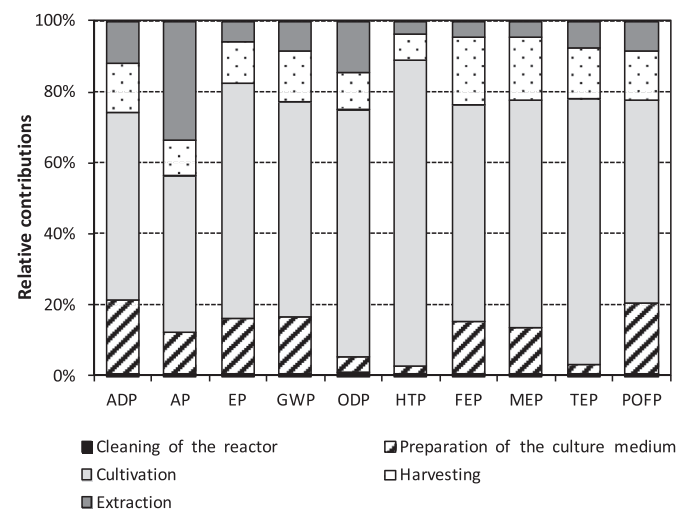


Fig. 3. Relative contribution (in %) per stage of lab-scale process to each impact category.

(cradle-to-gate perspective) at laboratory scale. A breakdown of the contribution of the production stages is depicted in Fig. 3 in order to identify the most relevant one for the selected environmental impact categories.

According to Fig. 3, the contribution from the cultivation stage is the main factor responsible for the environmental burdens derived from the production of astaxanthin with remarkable contributions of more than 44% to all impact categories under assessment. Among the less contributing stages, the preparation of the medium plays a significant role in categories such as ADP, EP, GWP or POFP, whereas the extraction is only relevant in terms of AP and ODP, and harvesting mainly contributes to ecotoxicity categories.

The contributing processes to each category are discussed below per impact category and stage and the environmental contributions are broken down in Fig. 4.

Abiotic depletion potential. The production of the electricity requirements was responsible for 53% of contributions to ADP, especially due to the consumption of electricity in the PBR (50% of total electricity, considering lighting and air blower). It shall be remarked here that the Belgian electricity profile depends considerably on fossil fuels, which was reflected on the ADP results. According to Fig. 4, the second most important factor responsible for abiotic depletion was the production of materials with a remarkable contribution of 33%, especially due to the production of polystyrene.

Acidification potential. The production of electricity and chemicals were the main contributors to AP (39% and 31% respectively). SO₂ emissions from coal power plants were the main responsible for the impact derived from the production of electricity. In the case of chemicals, the impact is mainly due to the manufacture of DMSO (99% of total AP), in which acidifying emissions of hydrogen sulphide are generated.

Eutrophication potential. The production of electricity requirements was again the main factor for eutrophying emissions and its contribution to EP was 51% of the total. In order of relevance, it was followed by waste treatment (17%) and aeration (14%).

Global warming potential. GHG emissions were mainly derived from the production of electricity requirements (61%). According to Fig. 3, the production of materials for the equipment and lab ware supplies contributed to 27% of GHG emissions. The main greenhouse gas responsible for the GWP was fossil CO₂ emissions (90%), especially derived from electricity production.

Ozone layer depletion potential. This category was affected up to 70% by the production of electricity, mainly due to its dependence

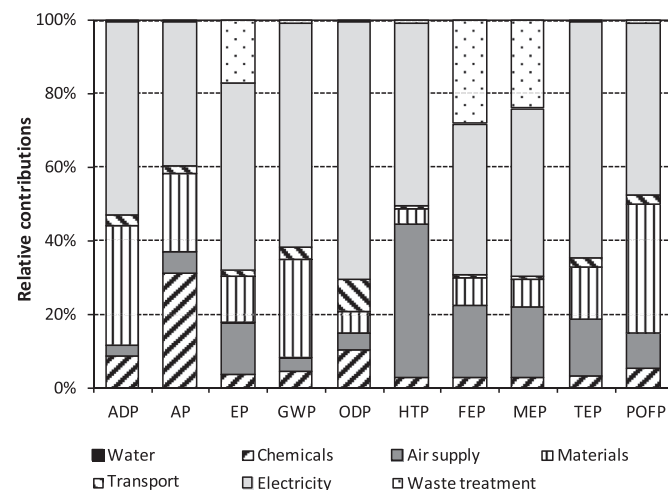


Fig. 4. Relative contribution (in %) per involved activity of lab-scale process to each impact category.

Table 5

Impact assessment results (characterisation step) associated with the pilot-scale production of 800 g of *Haematococcus astaxanthin* with two evaluated options for the cleaning stage in comparison with the corresponding impacts of the lab-scale process.

Impact category	Unit	Lab-scale process	Chemical disinfection	Ozone sterilisation
ADP	kg Sb _{eq}	572.89	13.6	13.6
AP	kg SO _{2eq}	355.76	12.1	12.1
EP	kg PO ₄ ³⁻ _{eq}	125.78	1.90	1.88
GWP	t CO _{2eq}	69.75	1.86	1.86
ODP	g CFC-11 _{eq}	3.83	0.130	0.129
HTP	kg 1,4-DB _{eq}	38886.69	321	319
FEP	kg 1,4-DB _{eq}	27029.44	261	259
MEP	kg 1,4-DB _{eq}	16166.48	190	188
TEP	kg 1,4-DB _{eq}	3.77	0.088	0.087
POFP	kg C ₂ H _{4eq}	12.32	0.490	0.490

on fossil fuels. The production of chemicals and the transport of inputs and waste are the most significant secondary contributors, with 10% and 8% of emissions, respectively. The main contributing substance was Halon 1211 (43%) emitted to air during the transport of natural gas in the production of electricity and DMSO.

Human toxicity. As in the previous categories, the production of electricity was the main factor which contributed to HTP with a ratio of 50%, followed by the compressed air required in the PBR (42%). This is caused by the emissions to air of arsenic (33%), chromium VI (27%) and polycyclic aromatic hydrocarbons (16%).

Ecotoxicity potentials. The contributing processes involved in these three impact categories follow the same trend as in other categories, where the production of the electricity was the major environmental key factor. Contributions in terms of FEP (41%) and MEP (45%) are associated with the emissions of vanadium, nickel and beryllium to water, especially coming from the disposal of materials in landfills. In the case of TEP, the impacts are mainly due to mercury (41%) to the air derived from the use of coal for electricity generation and chromium VI (32%) to the soil from the distribution network. Waste treatment showed a remarkable contribution in terms of FEP (28%) and MEP (24%), followed by air supply (20% and 19% to FEP and MEP, respectively).

Photochemical oxidants formation potential. The 47% of contributions to this category were due to the electricity consumption in the astaxanthin production process. The second most important factor was the production of materials for the equipments and lab ware supplies (35%). The main contributing substances to POFP were SO₂ (59%) and CO (15%).

3.2. Pilot-scale environmental profile

The characterisation results of the astaxanthin process at pilot scale are shown in Table 5 for the two options evaluated for the cleaning and sterilisation stage. In order to analyse the improvement of the pilot process in contrast with the information obtained at lab scale, the results of the lab process are also presented in terms of an identical functional unit. It must be remarked, however, that this would not be a realistic functional unit for a lab process and, thus, it is here used for comparative purposes, exclusively.

The obtained values show that there is no significant difference between the environmental impacts of both pilot-scale alternatives in all the assessed categories, although a slight improvement is observed for the case of ozone sterilisation. As the results differ in less than 1.5% for all impact categories, the following analysed contributions will be referred to the second option: ozone sterilisation, as this seems the most realistic scenario for a commercial scale plant.

Regarding the improvement with respect to the lab-scale process, environmental impacts of both pilot options were found between 25 and 122 times lower than the corresponding lab-scale impacts. According to the results, the most remarkable reductions correspond to the toxicity potentials, which were the categories with higher contribution of air supply and waste treatment activities in the lab-scale process. It must be highlighted that compressed enriched air used in the lab process was substituted by air from the environment as CO₂ source in the pilot system. In addition, toxicities were related to relatively important contributions of the harvesting stage, which was also modified in the pilot process.

According to Fig. 5, the contribution from the cultivation stage is again the main factor responsible for the environmental burdens derived from the production of astaxanthin with higher relative contributions than those of lab-scale process (more than 75% to all impact categories under assessment). Even so, impact reductions up to 95% were observed in all the evaluated categories with respect to lab-scale process, mainly related to the substitution of the cultivation in a single reactor by the two-stage cultivation process.

In the case of other stages, such as preparation of the culture medium or extraction, the relative contributions with reference to the total impacts of the pilot process have moderately decreased, probably due to the optimisation of the process and the different technologies applied. Particularly, supercritical technology has already been highlighted as a less energy-consuming separation alternative than organic solvent extraction (Aresta et al., 2004, 2005). Regarding this issue, Brentner et al. (2011) found an energy demand 4.5 times higher for hexane extraction than the corresponding value for supercritical CO₂, whereas supercritical methanol extraction allowed even reduced energy consumption, 5% lower than that of supercritical CO₂. In this case, the extraction stage of the pilot-scale process shows impact reductions of about 50 times lower than the lab process in most categories. The improvement is even more noticeable in the case of AP (1% of impact in pilot process with respect to total contribution of the lab-scale extraction). The main reason for this finding may be the removal of DMSO, associated with acidifying emissions of hydrogen sulphide during the production process.

The contributing processes to each category are discussed below per impact category and stage. The breakdown of the environmental contributions is presented in Fig. 6.

Abiotic depletion potential. The production of the electricity requirements for the pilot-scale process was responsible for 93% of

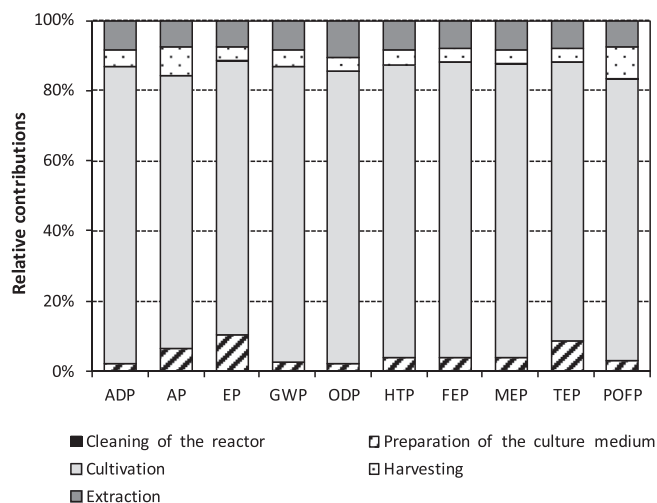


Fig. 5. Relative contribution (in %) per stage of pilot-scale process with ozone sterilisation to each impact category.

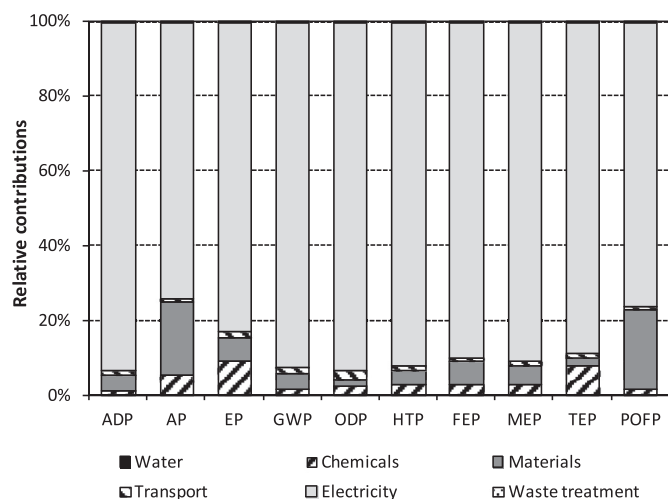


Fig. 6. Relative contribution (in %) per involved activity of pilot-scale process with ozone sterilisation to each impact category.

contributions to ADP, especially due to the consumption of electricity in the cultivation stage. On the contrary, the production of materials for the equipment, which had a remarkable contribution for the lab-scale process, was associated to only 4% of the impact of the pilot system. This significant decrease can be probably attributed to the scale economy that promotes a more intensive use of the equipments for a longer period of time. All the other processes also had very slight contributions, being the production of the materials for the equipments the most relevant one (4%).

Acidification potential. The production of electricity was again the main contributor to AP (74%). SO₂ emissions from coal power plants were the main responsible for the impact derived from the production of electricity. In this case, the relative impact of the chemicals was noticeably reduced (from 34% to 5%) thanks to the use of supercritical CO₂ extraction instead of conventional solvent extraction. Regarding the production of materials, the reduction of this contribution with respect to that of the lab-scale case study was almost negligible (from 21% to 20%). Within this contribution, the use of stainless steel for the two photobioreactors used in the cultivation stage accounted for 58% of the impact.

Eutrophication potential. The production of electricity requirements was again the main factor for eutrophying emissions and its contribution to EP was around 83% of the total. Among the secondary processes, the production of the chemicals was the most relevant contribution (9%).

Global warming potential. A high percentage of GHG emissions (93%) were associated to the production of electricity requirements. The remaining processes had very limited contributions of less than 5% of the total impact each one.

Ozone layer depletion potential. The production of electricity was responsible of 93% of the contribution to this category, especially due to its dependence on fossil fuels. Once again, the other processes had no significant impacts, with less than 3% of the contributions. The main contributing substance was Halon 1211 (67%) emitted to air during the transport of natural gas used for energy production.

Human toxicity. This category was affected by the production of electricity in 92%, mainly caused by the emissions to air of arsenic (30%), polycyclic aromatic hydrocarbons (24%) and nickel (13%).

Ecotoxicity potentials. As in the previous categories, the production of the electricity was the major responsible of the environmental impacts to FEP (90%), MEP (91%) and TEP (89%). There was a remarkable reduction with respect to the lab-scale process in

the relative contributions of waste treatment to FEP (from 28% to 0.02%) and MEP (from 24% to 0.02%). Emissions of nickel and beryllium to water were the most contributing factors to FEP and MEP, whereas TEP was principally affected by emissions of mercury (29%) and vanadium (27%) to the air derived from the use of coal for electricity generation and chromium VI (23%) to the soil from the distribution network.

Photochemical oxidants formation potential. The 77% of contributions to this category were due to the electricity consumption in the pilot-scale production process. The other significant contribution came from the production of materials for the equipments (21%). Emissions of SO₂ associated to the use of fossil fuels accounted for 76% of the impact in this category.

3.3. Improvement scenarios

According to the results shown in the previous section, the production of electricity required within the whole life cycle of the astaxanthin production at lab and pilot scale dominated the environmental burdens in all the impact categories. Several processes involved in the lab-scale process had significant contributions in some specific categories (e.g. materials affected considerably to ADP and POFP, waste treatment had a relevant impact in FEP and MEP). Nevertheless, the only secondary process that had relevant contributions to some categories in the case of pilot-scale system was the production of materials for the equipments, which affected to AP and POFP.

No straight-forward comparison between the results from this study with others from available literature can be made due to the lack of reports regarding the production of high-value added products from microalgae. Up to date, the related papers on microalgal LCA aim the identification of the environmental performance of biodiesel production from microalgae (Brentner et al., 2011; Lardon et al., 2009; Stephenson et al., 2010).

3.3.1. Sensitivity assessment of electricity requirement

According to Stephenson et al. (2010) and Jorquera et al. (2010), the choice of cultivation system (e.g. airlift tubular bioreactor, raceways, ...) considerably influences the environmental results associated to microalgal production (specifically in terms of energy requirements and GWP) as cultivation represents the most intensive energy stage over the life cycle of biodiesel production (cradle-to-grave perspective). Fig. 7 shows a breakdown of the contribution of the electricity for all the stages of the production process that have consumption higher than 1% of the total. According to the results, the two-step approach for cultivation is responsible for the

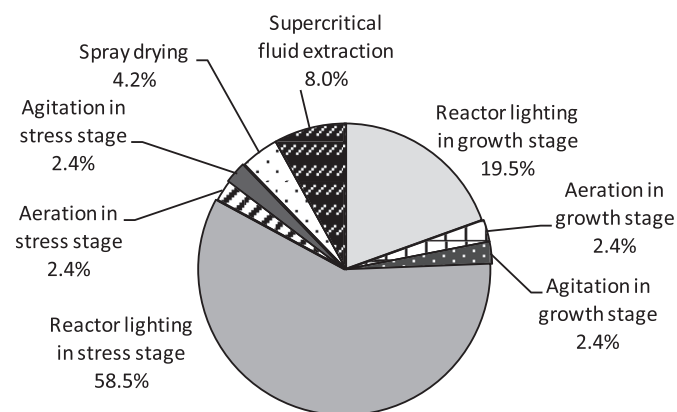


Fig. 7. Relative contribution of the electricity requirements per stage to the total environmental impact of the pilot-scale production of astaxanthin.

highest ratios of the environmental burdens derived from the electricity production, due to the high light intensity requirements. Both stages need 82% of the total electricity consumption (20% associated to the growth stage and 62% for the stress stage), while any of the other stages contributes less than 10% to the impact.

It could be possible to propose improvement alternatives in order to reduce the electricity requirement in the bioreactor. However, not only the electricity requirement must be taken into account in a decision process but also other important variables such as water consumption, contamination risks, light utilisation rate as well as the production yield and capacity. This is the case of the ORPs which commonly require less electricity but present lower culture productivity. Obviously, for practical, economic and environmental reasons, sunlight is preferred in extensive systems (Pruvost et al., 2011). In this pilot-scale process, two airlift PBRs were used for the experiment using artificial illumination. The use of solar illumination could be a cheap alternative although it presents limitations due to the diurnal fluctuations of light intensity that may result in a decrease in the total biomass concentration as high as 35% (Chen et al., 2011; Ogbonna et al., 1999). Specifically in Ireland, algae can only be produced outdoors for less than five months a year and to work all the year, the installation should be moved indoors and use artificial lighting. Moreover, it is important to point out that the number of days required to obtain the same amount of microalgae cell paste under solar light conditions are considerably higher than under artificial illumination since the growth of microalgae and the composition of biomass are strongly dependent on the light supply (light source and light intensity) (Ogbonna and Tanaka, 2000; Yeh et al., 2010). For these reasons, closed controlled indoor photobioreactors illuminated with artificial light are being currently applied for high-value products including astaxanthin (Lorenz and Cysewski, 2000; Patil et al., 2008).

Several related studies have analysed and compared differences on energy requirement and operational parameters between different types of PBRs under solar radiation (Brentner et al., 2011; Jorquera et al., 2010; Sierra et al., 2008). Based on these results, a sensitivity assessment was carried out considering other alternatives for the PBRs used here, which have been considered as internally illuminated annular photobioreactors according to productivity and electricity requirements. In this study, artificial illumination is supplied to the PBR by means of fluorescent bulbs for 8 days and 16 h·day⁻¹ for the growth stage and for other 8 days and 24 h·day⁻¹ for the stress stage. According to Brentner et al. (2011), reductions up to 96% in the energy consumption can be achieved if flat-panel PBRs are used instead of annular PBRs when solar radiation is used as light source and considering the same amount of biomass production. Moreover, we have also considered a reduction in the biomass and astaxanthin yields taking into account the highest residence times required in a PBR under sunlight conditions in comparison with artificial light in order to obtain identical levels of biomass (Pruvost et al., 2011). Since the exposure to solar light is only diurnal (~10 h per day), it was assumed a reduction on the biomass production for the same period of time as in annular PBRs under artificial light (8 days for each cultivation stage) of 50% for each of the annular PBRs under sunlight. Based on Brentner et al. (2011), algal cultivation in flat-panel PBRs require the same residence time than in annular PBRs under identical conditions. Consequently, it was assumed the same production of biomass in both annular and flat-panel PBRs.

Therefore, in the sensitivity assessment, annular and flat-panel PBRs with sunlight have been proposed as potential alternatives to the artificially illuminated PBRs, assuming no differences in other LCI data (Brentner et al., 2011). The scenarios proposed would be the following:

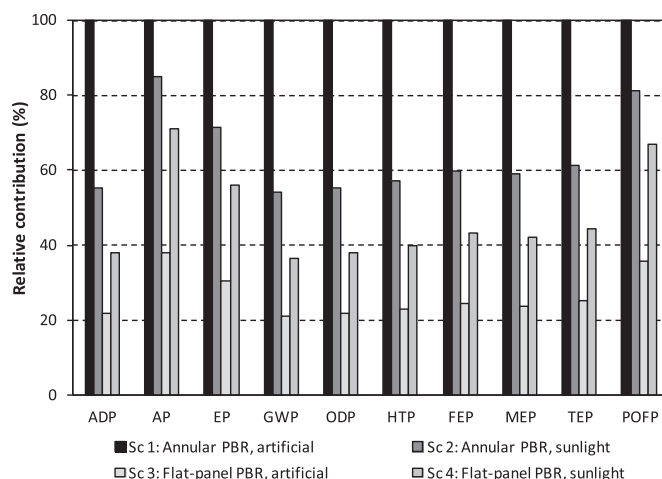


Fig. 8. Sensitivity analysis of the environmental performance considering four different configurations for the two PBRs: annular and flat-panel PBRs with artificial or solar illumination.

- Sc 1: annular PBRs with artificial light in growth and stress stages and 800 g of astaxanthin production
- Sc 2: annular PBRs with sunlight in growth and stress stages and 400 g of astaxanthin production
- Sc 3: flat-panel PBRs with artificial light in growth and stress stages and 800 g of astaxanthin production
- Sc 4: flat-panel PBRs with sunlight in growth and stress stages and 400 g of astaxanthin production

Although longer life spans for the reactor materials are expected for the flat-panel PBRs (50 years in comparison with 40 years considered for the annular PBRs) as well as larger required areas for similar biomass yield, these values have not been taken into account due to their minimal contribution to most of the impact categories. Fig. 8 shows the comparative environmental result per impact category and PBR models assumed. According to the results, all the proposed scenarios would allow significant environmental benefits with respect to the case study. In the first alternative scenario, in which the use of annular PBRs was considered and artificial illumination was substituted by sunlight illumination, the obtained improvements were limited between 15% and 46% (for AP and GWP respectively). For the flat-panel configuration with sunlight illumination, reductions of impact ranged from 29% to 64%. The ideal situation would be the use of two flat-panel PBRs with artificial illumination, which would permit a decrease between 62% and 79% of the impacts in all categories.

3.3.2. Exploitation of co-products from residual algal paste

Due to the potential uses of astaxanthin, this paper was focused on its natural production (at lab and pilot scale) by the green microalgae *H. pluvialis*. Although the main objective in the process is the production of this carotenoid, a co-product from the extraction stage known as “algal paste” also has potential applications for biodiesel production due to its fatty acids content. Alternatively it could be feedstock for an anaerobic digester or used as a fertiliser (Campbell et al., 2011). Although it was not taken into account within the system boundaries, further research should be paid on the algal by-products.

4. Conclusions

Nowadays special interest is being paid to microalgal production for several reasons: sustainable energy, foodstuffs, industrial

chemicals, pharmaceuticals and/or nutraceuticals production. The life cycle impacts of microalgae cultivation considerably depend on the production scale, according to the results presented in this study. Moreover, several remarkable improvements observed in the pilot process can be related to changes implemented in the system as a result of lab-scale environmental assessment, such as the substitution of compressed air supply or the use of supercritical CO₂ extraction as a more suitable separation technique. In the lab-scale process, several inputs affected the environmental profile, whereas in the case of pilot system, electricity dominated the contributions to all categories.

The choice of the photobioreactor considered for the algae cultivation stage is one of the most important environmental issues to be taken into account due to the large differences of electricity requirements. Moreover, if the microalgae are cultivated in order to obtain a specific compound such as carotenoids, the extraction method considered, whether it is based on organic solvents or supercritical fluids, has significant influence on the environmental results. Due to the high contribution of the electricity, a sensitivity assessment was proposed in order to identify the best reactor configuration for the *Haematococcus* astaxanthin production system from an environmental point of view. According to the results, the scenarios based on the use of sunlight instead of artificial illumination allowed significant reductions of impact. However, the improvements observed in these cases were limited by the decrease in biomass productivity associated with sunlight culture systems. Therefore, the optimal production system would consist of two flat-panel PBRs with artificial illumination, which would allow reductions between 62% and 79% of the impact depending on the considered category. As this study included the evaluation of a pilot-scale process, the results allow the identification of specific environmental hot spots which are likely to affect the industrial scale processes and, thus, that must be solved before the implementation of the commercial process. Technological advantages are rapidly occurring in the microalgae-related industries. The results of this paper should be considered in order to produce in a more sustainable manner not only *Haematococcus* astaxanthin but also other microalgae derived compounds.

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Acronyms

ADP	abiotic depletion
AP	acidification
DMSO	dimethyl sulfoxide
EP	eutrophication
FEP	freshwater aquatic ecotoxicity
GHG	greenhouse gas
GWP	global warming
HTP	human toxicity
LCA	life cycle assessment
LCI	life cycle inventory
MEP	marine aquatic ecotoxicity

ODP	ozone layer depletion
ORP	open raceway ponds
PBR	photobioreactor
PVC	polyvinyl chloride
POFP	photochemical oxidants formation
TEP	terrestrial ecotoxicity

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