Sustainability Assessment of Blue Biotechnology Processes: Addressing Environmental, Social and Economic Dimensions

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Abstract The biotechnological development has traditionally focused on the compliance with regulatory demands rather than optimising the processes or analysing their sustainability. This work proposes the combination of available tools for the comprehensive sustainability assessment of a blue biotechnology process based on the cultivation of the microalgae *Haematococcus pluvialis*. The work aims to include environmental, economic and social dimensions to measure the sustainability of the production of a carotenoid with potential applications in food, nutraceutical, cosmetics and eventually pharmaceutical industries. Electricity for cultivation was identified as the major contributor to the environmental impacts, which depended significantly on the production scale. Social benefits were mainly related to workers and consumers, while the economic assessment suggested a profitable process with a relatively short period to recover the initial investment.

1 Introduction

Biotechnology is a wide industrial sector that ranges from high value, low volume products such as pharmaceuticals to low value commodities such as biofuels. The main effort to date has focused on implementing processes effectively to meet the regulatory demands more than optimising the operations or analysing the sustainability, especially in the case of fine chemicals [1]. Nevertheless, there have been several attempts to develop methodologies for the measurement of bioprocess sustainability in the last decade [2, 3].

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Life Cycle Assessment (LCA) is one of the available methodologies to measure this sustainability holistically, although few LCAs applied to bioactive compounds and pharmaceutical ingredients are found in literature [2–4]. In the case of blue (i.e. marine) biotechnology, which involves the exploration and exploitation of new products from marine organisms, the LCA studies conducted to date mainly analysed the cultivation and extraction of fractions from microalgae and seaweed. They focus on relatively low value commodities, namely biofuels [5]. Most of the work dealt with the production of biodiesel by transesterification, although other bioenergy sources (bioethanol, biogas …) have also been evaluated. Few examples of LCA studies addressing the production of high-value chemicals and bioactive compounds from marine sources are available, due to the lack of information from commercial-scale facilities [4, 5]. The studies generally rely on extrapolations and simulation models rather than field data from operating systems [5].

According to the principles of sustainable development, measuring sustainability for supply chain decision-making requires the integration of social and economic dimensions together with environmental aspects [6]. To this end, an integrated framework for Life Cycle Sustainability Assessment (LCSA) is proposed. It combines conventional LCA with social LCA (SLCA) and Life Cycle Costing (LCC) [7], based on UNEP/SETAC guidelines [8] for SLCA and [9, 10] for LCC.

In this work, the sustainability of a blue biotechnology process, namely the production of the red carotenoid astaxanthin by the green microalga *Haematococcus pluvialis*, is evaluated. Astaxanthin is a high-value red carotenoid with numerous applications in food and feed industries, nutraceuticals and cosmetics [11]. Given its antioxidant and anti-inflammatory properties, astaxanthin is suggested to play a beneficial role in human health for the protection of skin cells against UV-light photo-oxidation, slowing of age-related diseases and even control of carcinogenic processes [11, 12]. Astaxanthin can be obtained from microalgae in a two-stage process: in the first stage the biomass is cultivated in a photo-bioreactor (PBR) under favourable growth conditions whereas in the second stage, adverse conditions are promoted to induce the accumulation of astaxanthin within the biomass [13].

A comprehensive sustainability assessment is here presented, based on process data from real facilities for algae cultivation and astaxanthin extraction at lab, semi-pilot and pilot scale. An environmental LCA jointly with a socio-economic assessment was conducted following SLCA existing guidelines and a Cost-Benefit Analysis (CBA) approach to complete the evaluation by taking the three dimensions of sustainability into account.

2 Methodology

The three dimensions of sustainability (environmental, social and economic) are evaluated in this work according to a cradle-to-gate perspective based on the Life Cycle Thinking principles. The environmental LCA followed ISO14040 standards [14]. A socio-economic assessment was conducted following UNEP/SETAC SLCA guidelines and CBA approach to complete the assessment [7–9].

2.1 Environmental LCA

The environmental performance of microalgal astaxanthin production was evaluated by conducting an attributional LCA with a cradle-to-gate approach. The study included the environmental burdens associated with the production of the different inputs to the system, the microalgae cultivation, harvesting and final carotenoid extraction. This process competes with two alternative routes that consist in: (i) the synthetic production from petrochemical feedstock and (ii) the fermentation process by the yeast *Phaffia rhodozyma* [15]. Although synthetic astaxanthin dominates the current market and has a more competitive price, it is not approved for human consumption as a nutraceutical or pharmaceutical. Recent studies suggest that the antioxidant activity of natural astaxanthin is significantly higher [11]. Thus, both the microalgae- and the yeast-based routes are suitable for its production, although microalgae process tends to have a higher yield.

The goal of the LCA was the identification of the main stages contributing to the environmental impacts of a nutraceutical oleoresin containing 10% astaxanthin while taking the influence of scale-up into account. Three real facilities were analysed, including a lab-scale system (15 L tubular airlift PBR), a semi-pilot system (80 L annular PBR) and a pilot system (1000 L sequential airlift PBRs). The production system was divided into 5 stages depicted in Fig. 1: (i) cleaning and sterilisation, (ii) preparation of the inoculum and culture medium, (iii) cultivation, (iv) harvesting and (v) extraction. The functional unit (FU) was defined as 1 kg astaxanthin, considered as a realistic production level for the pilot-scale process. Although this FU was not a realistic value for the lab process (which produces approximately 1 g per batch), the results are referred to the same unit as the pilot systems to facilitate the comparison of the environmental profiles.

The Life Cycle Inventory (LCI) data for the foreground system consisted of average data obtained by on-site measurements. Water emissions were calculated assuming that the remaining nutrients in the culture medium after algae growth were directly discharged to water. Data for the background inventory were taken from Ecoinvent v2.2 [16]. A system expansion approach was considered to include the potential use of residual algal biomass as fertiliser. The biomass content of nitrogen and phosphorous were calculated according to [11].

The Life Cycle Impact Assessment included the classification and characterisation stages, which were conducted according to CML 2 baseline 2001 V2.05 impact categories [17]. Environmental indicators of ten impact categories were evaluated: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential over a 100-year timeframe (GWP), ozone layer depletion potential (ODP), photochemical oxidants formation potential (POFP) and toxicity related impact categories: human toxicity (HTP),

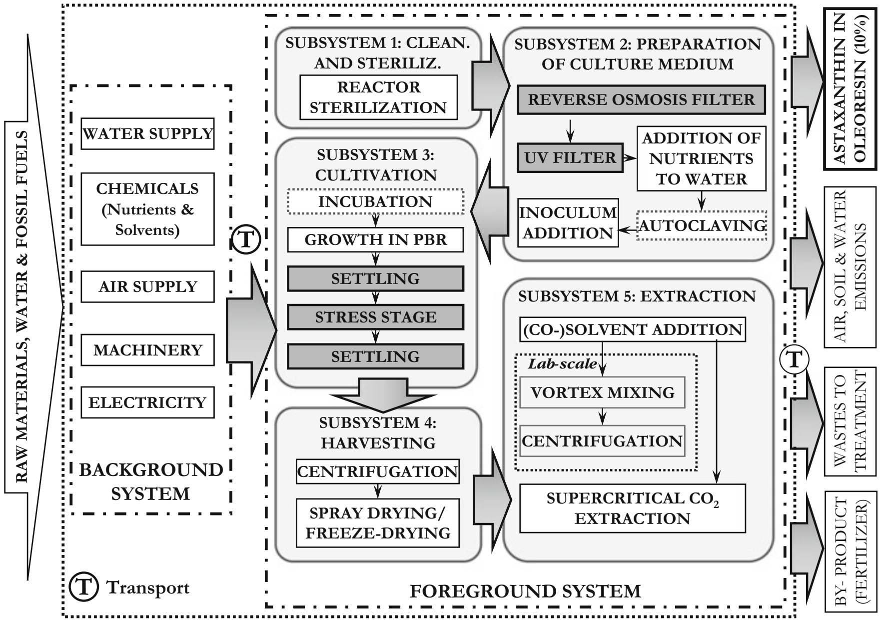

Fig. 1 Process chain and system boundaries for the production of *H. pluvialis* astaxanthin (blocks in dark grey correspond to steps that are specific to the pilot-scale production, blocks with dotted lines correspond to steps that are specific of lab- and semi-pilot production)

freshwater aquatic eco-toxicity (FEP), marine aquatic eco-toxicity (MEP) and terrestrial eco-toxicity (TEP). SimaPro 8.0.2 was used for the implementation [18].

2.2 *Social Assessment*

The social dimension is frequently considered as the weakest pillar of sustainable development, as reflected by the limited analytical and theoretical tools for its evaluation [19]. In order to develop a standardized methodology, UNEP-SETAC published the Guidelines for Social Life Cycle Assessment of Products, together with the methodological sheets for subcategories in Social Life Cycle Assessment (SLCA) [8, 20]. The methodological sheets contain all the necessary information to collect data for 31 defined impact sub-categories, which correspond to relevant characterised social issues. The sub-categories representing social impacts are classified into five stakeholder categories: workers, consumers, local community, society and value chain actors. The given information includes a definition of each sub-category and an explanation of issues associated with it, as well as examples of inventory indicators, units of measurement and data sources [20].

In this case, the methodological sheets were taken as a basis to perform the social assessment of the *H. pluvialis* astaxanthin production. Thus, a specific questionnaire was developed, dealing with key issues and possible indicators related to the sub-categories that were relevant for the scope of the assessment. The questionnaire was fulfilled by two small and medium enterprises (SMEs) located in France and Ireland. For confidentiality reasons, the companies are referred to as SME 1 and SME 2 in the results section.

Three stakeholder groups were considered as the most representative in the specific context of the study: workers, consumers and society. For each of them, the selected indicators were grouped into sub-categories and measured in quantitative or semi-quantitative terms. Indicators for workers included annual salary, women-to-man ratio considering the total number of employees of each SME, women-to-man salary difference for the country and working hours per week. For consumers, impacts and benefits of the product were measured in terms of tests and safety information provided, customer service and information on formulation and use, value added of the product, natural origin, etc. Indicators for the society included the relative importance of blue biotechnology in the country, potential market share for the studied companies, compliance with certifications, existence of signed codes of conduct on sustainability, etc.

Following the approach of previous social LCA works [21], each indicator was expressed according to a numeric index based on the risk level in order to better understand the social impact information. As shown in Fig. 2, the index for each indicator ranged from 1 to 4, being 1 the corresponding value for the worst scenario (highest risk) and 4 the index for the ideal scenario (no risk at all). In the case of stakeholder "workers", all the selected indicators were quantitative. The index for each indicator was calculated with respect to minimum and maximum risk levels in the world according to the values reported by OECD [22], Statista [23] and the World Economic Forum [24]. For each subcategory, the index was then obtained as the average index of the set of indicators assigned to this subcategory. For the stakeholders "consumers" and "society", most indicators had a Yes/No format; therefore, all the impacts related to these subcategories were converted into semi-quantitative terms through a scoring system. For Yes/No indicators, a value of 1 was assigned to negative response and a value of 4 was considered for affirmative response. In the case of some specific indicators, intermediate values were assigned according to expertise knowledge.

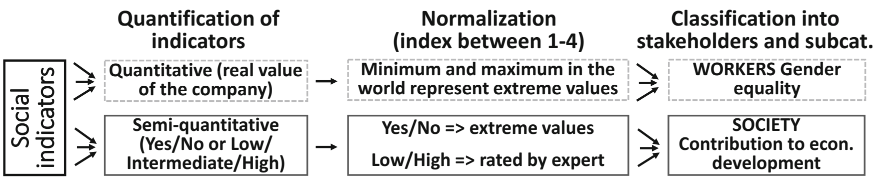

Fig. 2 Scheme of the method applied for the social impact assessment

2.3 Economic Analysis

As economic aspects cannot be neglected in life cycle based sustainability assessment, a CBA approach is here proposed to evaluate this dimension. CBA is a basic decision-making tool included by Huppes et al. [9] among the methods to address the economic dimension of sustainability. It allows the comparison between different proposals according to the net profit of each option. As the integration of both CBA and LCA is now being widespread for the combined assessment of economic and environmental aspects [10, 25], this methodology has been selected for the evaluation of astaxanthin production.

CBA aims to compare the economic feasibility of a project or process by taking into account the costs and benefits over its life time [10, 25]. The starting point of the tool is the premise that a project should only be developed if all the benefits exceed the aggregated costs. This premise is checked out by considering the net profit of a process as the difference between benefits and costs:

$$NP = \sum B_i + \sum C_i \tag{1}$$

Where NP is the net profit, Bi > 0 is the value of the benefit item i and Ci < 0 is the value of the cost item i. Thus, if the result of the calculation is NP > 0, then the project is economically viable, whereas if NP < 0 the project is not viable in economic terms. The implementation of CBA requires that all benefits and costs are expressed in the same units. In projects related to environmental issues (e.g. operation of wastewater treatment plants), this restriction may require a complex homogenisation method for the quantification in monetary terms. However, in the case of the addressed process, the only benefit corresponded to the production of a high value molecule with biological properties, so the benefits could be measured in the same units as for costs (monetary units) and no method of homogenisation was needed.

Firstly, the assessment followed the CBA approach proposed by [10] to determine the NP by only considering the benefit of astaxanthin production and the variable operating costs in terms of energy consumption, chemicals, staff and other raw materials. In a second stage, the economic feasibility of the process was evaluated by considering two additional parameters: the net present value (NPV) and the pay-back period. Four different types of internal costs were included for the study of economic feasibility throughout the whole life time of the project, whereas externalities were excluded to avoid double counting of issues already covered by the environmental LCA:

- Investment costs, including the equipment required for the operation of the plant.
- Overhead costs, related to renting, insurances, travel costs, taxes and interests.
- Variable operating costs (already considered in the first stage, in which NP was determined according to the approach of [10]) associated with the consumption

Fig. 3 Algorithm for the calculation of cash flows in the determination of the net present value of a project

(+) Revenue
(-) Variable operating costs
(-) Overhead costs
(-) Amortization
BENEFITS BEFORE TAXES
(-) Taxes
BENEFITS BEFORE INTERESTS
(-) Interests
NET BENEFIT
(+) Amortization
(-) Investment
NET CASH FLOW RATE

of water, chemicals and other raw materials (material costs), as well as energy, operating labor costs, and also disposal costs.

– Research and development costs (calculated in relation to revenue).

With this information, the NPV was calculated according to Eq. 2:

$$\text{Total } NPV \text{ of the project} = \sum_{n=1}^{n=t} \frac{\text{Cash flow in year t} \cdot (1+\mathrm{i})^n}{(1+\mathrm{r})^n} \qquad (2)$$

Where “n” is the number of years of analysis, “i” is the inflation rate and “r” the nominal discount rate. The determination of cash flows was carried out according to the algorithm shown in Fig. 3.

The pay-back period of a project is defined as the period of time during which a facility must operate to recover the initial investment, according to the total capital costs and the estimated annual profits. It was determined by accumulating the annual profits until an equal value to the capital sum invested was obtained.

3 Results and Discussion

3.1 Environmental Performance of **H. pluvialis** *Astaxanthin*

The results of the environmental LCA for the astaxanthin production process are depicted in Fig. 4. According to the results, there is a strong dependence of the environmental impacts with respect to the production scale. Thus, the total contributions were found to be from 10% up to four times higher for the lab-scale process than for the semi-pilot system. Regarding the pilot two-stage process, the semi-pilot system was found to have impacts between 10 and 100 times higher, whereas the lab process showed contributions between 25 and 122 times above those of the pilot process. Differences between production scales are mainly linked to low yields and oversized equipment in the smaller-scale processes. These differences are expected to decrease as the production scale increases, until an

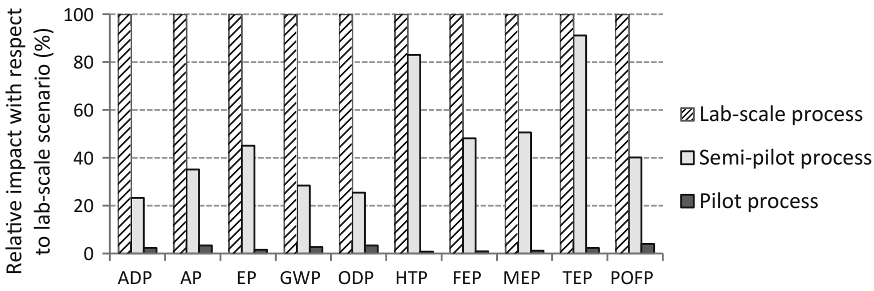

Fig. 4 Environmental LCA results associated with the production of 1 kg astaxanthin by *H. pluvialis* at lab, semi-pilot and pilot scale

asymptotic minimum level is achieved. Regardless of the environmental indicator and the production scale, most of the impact was linked to cultivation stage (S3). In particular, the production of electricity (mainly associated with artificial illumination and air supply) was the main hot-spot responsible for these environmental burdens, as further discussed in [11].

3.2 *Social Hotspots of* H. pluvialis *Astaxanthin*

The indexes for the selected social indicators of each stakeholder category were aggregated by sub-category and depicted in a spider chart (Fig. 5) to obtain a visual representation and identify the hot spots or main social concerns of the process. As shown in Fig. 5, the results of the social impact assessment show the profiles for both SMEs, with most indexes near the maximum possible value. However, the outcome differs depending on the strategic management of the company and on the

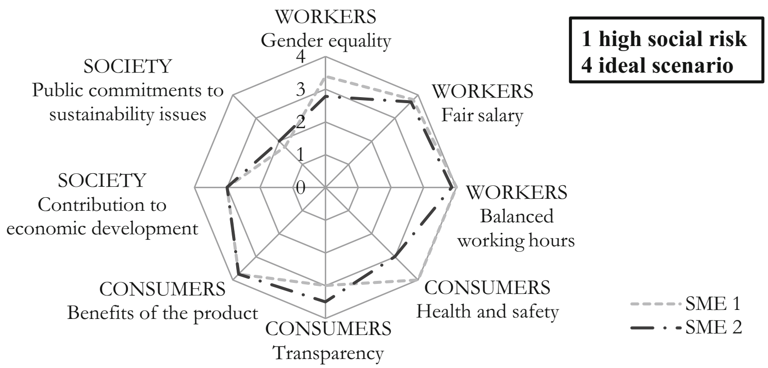

Fig. 5 Radar chart representing prominent social issues of the corporate strategy of two SMEs involved in the production of *H. pluvialis* astaxanthin

considered stakeholder category. Thus, while the performance related to workers and consumers show quite different profiles for the two companies, the sub-categories related to society present a similar behaviour. Nevertheless, the score of both companies in terms of benefits to workers and consumers revealed a relatively favourable performance. Despite the importance of the respective countries in a national scale, the performance in terms of benefits to society was, in the specific case of the evaluated SMEs, limited by the small size of the two companies, which resulted in a low potential market share, compared to the total market volume of blue biotechnology in the corresponding countries.

3.3 Economic Evaluation of H. pluvialis *Astaxanthin*

The NPV was obtained considering a production of 120 kg astaxanthin/year, a 12.5% nominal discount rate (according to typical values of 10–15% for biomass products) and a 1.7% inflation rate (average inflation rate in the country for the year 2012). The calculated value was 2,068,203 €, which means that the assessed process would be economically feasible, since NPV > 0. Among the different groups of costs, the variable production costs were responsible for up to 75% of the total cost. The highest fraction of these variable operating costs corresponded to the staff, which represented more than three fourths of the production costs. Among the other items, energy consumption would be the most relevant cost, with 20% of the total. Regarding the pay-back period, Fig. 6 shows that one year and four months of operation of the facility, would be a sufficient period of time to recover the total initial investment according to the estimated costs and revenues.

The results obtained for the two indicators (net present value and pay-back period) indicate that microalgal astaxanthin could allow significant economic benefits. Although the performed economic assessment is subject to a considerable level of uncertainty, related to the inaccurate estimation of the different costs and final revenue for a sector that is still immature, the high profitability and low payback time suggest that the process would still be viable in a wide range of conditions (including less favourable contexts). Additional co-products may be obtained from the residual algal paste in the future, increasing the potential revenues of the process.

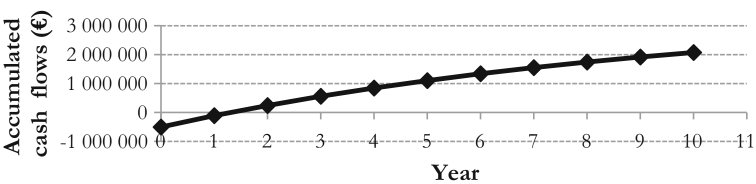

Fig. 6 Pay-back period for astaxanthin production at pilot scale

4 Conclusions

In this study, the existing tools to estimate the environmental, social and economic performances were applied to a novel production process in the sector of blue biotechnology. The results allowed evaluating the high influence of upscaling in the environmental profile of microalgal production process, as well as identifying the main contributors to the environmental impacts (electricity related to cultivation stage). The results also indicate that the process may have remarkable societal benefits (especially for workers and consumers) and the economic indicators suggest that the process could be feasible if operated under similar conditions as in the case of the studied SMEs. The combined outcome of the environmental, social and economic assessment of microalgal astaxanthin production constitutes a valuable basis for the successful incorporation of sustainability criteria in the design of blue biotechnology processes. The results may help to orient actions towards a more eco-efficient microalgae-related industry as well as to feed the debate for the development of appropriate environmental and socio-economic policies in the sector.

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