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Commercial astaxanthin production derived by green alga *Haematococcus pluvialis*: A microalgae process model and a techno-economic assessment all through production line

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ABSTRACT

The freshwater green microalgal strain *Haematococcus pluvialis* is the richest source for the production of astaxanthin. Astaxanthin is member of the xanthophyll family of carotenoids and constitutes the highest value product derived by microalgae. So far, algal astaxanthin amounts to <1% of the global market, since the synthetic alternative involves lower production costs. In this study, the technical and economic performance throughout large scale astaxanthin production, for two European cities (Livadeia, Greece and Amsterdam, the Netherlands), is investigated. The techno-economic assessment was facilitated by creating a theoretical process model, which simulated all phases of the production process. A hybrid system for photoautotrophic cultivation comprised by a photobioreactor (PBR) fence and a raceway pond complex was assumed for the 'green' and the 'red stage' respectively. The area covered by each cultivation system was assumed as 1 ha. The technical part included the mass-energy flows associated with the production process. The most important mass inflow refers to freshwater. More specifically, 63,526 m^3/year and 23,793 m^3/year are needed for the production of 426 kg/year and 143 kg/year astaxanthin in Livadeia and Amsterdam respectively. Regarding total energy needs, they were calculated at 751.2 MWh/year and 396.5 MWh/year for the Greek and the Dutch city respectively. With respect to the economic performance, a Profit and Loss (P&L) analysis was conducted applying three scenarios (worst-, base- and best case). Determining CAPEX and annual OPEX, the return of investment (ROI) for different market prices of astaxanthin was calculated. It was found that only in Livadeia high economic viability can be achieved for all market prices. The costs per kilogram of natural astaxanthin for Livadeia and Amsterdam were calculated at €1536/kg_{ASTAX} and €6403/kg_{ASTAX} respectively (best case scenario), rendering natural astaxanthin unable to compete with the synthetic alternative (€880/kg_{ASTAX}) yet, at least for feeding purposes.

1. Introduction

As global population and consequently energy demand increase over time the introduction and commercialization of renewable sources of energy becomes a critical issue. Microalgal biomass as feedstock for bio-energy production is an attractive alternative to bio-energy derived from terrestrial plant utilization [58]. Nonetheless, microalgae cultivation solely for bio-energy generation purposes seems not yet to be economically feasible [8,17,49,80]. Therefore, other applications of microalgae have been investigated. Microalgae, cultivated under specific stress conditions, can accumulate, along with the lipids and carbohydrates, considerable amount of secondary metabolites, whose industrial exploitation strongly enhances a bio-based economy [57].

Among these metabolites, the carotenoid pigment astaxanthin is considered to be one of the most valuable algal compounds with a wide range of applications in the food, feed, cosmetics and pharmaceutical sector [8,14,49,78]. Astaxanthin ($C_{40}H_{52}O_4$, 3,3′-dihydroxy-β,β′-carotene-4,4′-dione) is a member of the xanthophyll family of carotenoids and is ubiquitous in fresh/saltwater [57,111]. It is a substance best known for giving the pinkish-red hue to the flesh of salmonids (salmons and trouts), shrimps, lobsters and crayfishes, while it displays a central role for their immune-system and positively impacts their fertility [49]. From the nutritional point of view, astaxanthin is considered as the most powerful antioxidant in the nature, serving the role of a highly efficient scavenger of free radicals build up within the human body [49, 67]. Astaxanthin is a substance that protects the skin against UV-induced photo-oxidation and it is used for anti-tumor therapies and prevention - treatment of neural damage interrelated with age-related macular degeneration, Alzheimer and Parkinson diseases [14,110]. Furthermore, it is considered as a natural superfood destined to enhance

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athletic performance by increasing stamina and reducing the time of muscle recovery [13].

Nowadays, the market value of astaxanthin varies usually from \$2500–7000/kg, while its global market potential was estimated at 280 metric tons and was valued at \$447 million in 2014 [8,49,43,61,78]. Of this market, more than 95% refers to synthetically derived astaxanthin, since it involves lower production costs (around \$1000/kg) than the algal alternative, which accounts to < 1% of the commercialized quantity [49,52,78]. Synthetic astaxanthin is produced from petrochemical sources, which raises the issues of food safety (potential toxicity in the final product), pollution, and sustainability [52,61]. In fact, to date, synthetic astaxanthin can only be used as an additive to fish feed for pigmentation purposes and has not been approved for direct human consumption in food or supplements [52]. Thus, as society, nowadays, stimulates a transition towards 'green solutions' and natural products, while global market is estimated to exceed \$1.5 billion by 2020, algae-derived astaxanthin seems to be gaining potential in the market [68,78].

Hitherto, there is scarce scientific research on the performance and viability of large scale astaxanthin production lines exploiting microalgae [52,78]. Most publications focus on the different ways to optimize technologies on laboratory-pilot scale without assessing commercialization, and/or if natural astaxanthin could compete with the synthetic alternative in the forthcoming years. This is the knowledge gap that this paper aims to fill. Furthermore, this study could also be of use for those who investigate commercialization of other microalgae products, such as biofuels.

2. Methodology

In this study a process model was created simulating large scale production of natural astaxanthin. The model calculates areal biomass-astaxanthin productivity and constituted the benchmark in order to determine the theoretical mass and energy flows all through the three phases (cultivation, harvesting, extraction) of the production process as well as to assess economic performance of such ventures.

2.1. Process model

2.1.1. Description

Microalgae cultivation constitutes the most important phase within the process. A successful cultivation results in a 'healthy' highly concentrated algal broth, which can further be processed for the recovery of the desired metabolites. Thus, the core of the process model refers to microalgae cultivation. In this paper, modeling cultivation phase is based mostly on previous attempts to simulate algae growth theoretically [44,46,89,90]. There are different nutritional modes to cultivate microalgae. In this paper, natural photoautotrophic metabolism is investigated. It involves the use of sunlight as energy source and inorganic Carbon as the Carbon source for the formation of biochemical energy through photosynthesis [41]. Before being captured by an algal cell to be metabolized, incident light is subjected to various inefficiencies and loss mechanisms. Further parameters that vigorously affect algal productivity refer to temperature and nutrients uptake (see Section 3.1).

After cultivation phase, harvesting and extraction phases take place. The goal of these phases revolves around the dewatering of the 'wet' biomass and the recovery of the pigment. There is an abundance of methods that can be employed during harvesting and extraction. A comparative research was conducted to result in the most appropriate combination of methods for the production of astaxanthin [75]. These methods were introduced into the process model in the form of recovery efficiencies (see Sections 3.2 and 3.3).

2.1.2. Regional scenarios

In photoautotrophic metabolism algae cells proliferation depends directly on the levels of solar irradiance, and significantly high or low values may result in an adverse impact on algal biomass productivity and the desired metabolite accumulation. Therefore, regional scenarios are necessary. In this paper, two European cities, Livadeia, Greece (38°43′33″ N/22°86′67″ E) and Amsterdam, the Netherlands (52°36′67″ N, 4°90′00″ E), are chosen for investigation. The main reason of this choice was to delineate fluctuations regarding astaxanthin productivity in two locations from the same climatic zone (temperate zone) but with significantly different latitude. As main model input, detailed climate data (irradiance and temperature data) throughout a calendar year (2014) were used in order to determine biomass productivity in the two cities, from which astaxanthin is derived. For Livadeia, ETHER, a company focused on photovoltaic parks and the National Observatory of Athens (NOA) provided the appropriate climate data. For Amsterdam, the climate data were derived by the official website of Royal Netherlands Meteorological Institute (in Dutch Koninklijk Nederlands Meteorologisch Instituut-KNMI).

2.2. Mass-energy flows

In this theoretical study, the mass and energy flows all through production process were calculated, using the annual biomass-astaxanthin productivities as benchmarks. The mass flows refer to the in- and outflows of the different substrates, while the energy flows refer to the direct energy consumption of equipment within the system boundaries (see Sections 4.2 and 4.3).

2.3. Economic performance

With regard to the economic evaluation, a Profit and Loss (P&L) analysis was conducted applying three scenarios (worst-, base- and best case). The costs throughout the production chain of astaxanthin referred to the capital- (CAPEX) and operational expenditures (OPEX). CAPEX included equipment costs and fixed capital costs, while the project lifetime is assumed as 10 years. OPEX refers to all costs in order the production line to operate, and was derived from cost analysis based on the mass-energy flows associated with the different systems that build the bio-refinery along with labor, maintenance and insurance. The profits were determined by the market prices for astaxanthin and residual biomass. The P&L analysis resulted in a financial statement that calculated the return of investment (ROI) for the selected locations. The costs per kg of astaxanthin were calculated as well.

Fig. 1 summarizes the methodology that was followed, delineating all stages of the research and including the key parameters of the process model as well.

3. Construction of the process model

3.1. Cultivation phase

3.1.1. Species and culture system

There are several microalgae strains that are reported as potential feedstock to produce astaxanthin, such as *Chlorella* sp., *Chlorococcum* sp. and *Scenedesmus* sp. [22,56,79]. Nevertheless, the accumulation of astaxanthin inside *Haematococcus pluvialis* cells exceeds any other known microalgae species (up to 4% of dry biomass) and thus it is the most preferred one for large scale natural astaxanthin production [112].

H. pluvialis is a freshwater strain of green microalgae with a very unique life, which is divided in two stages [10]: The first refers to a green, motile vegetative stage, in which the microalgal cells continuously divide and proliferate, synthesizing chlorophyll. During this stage full nutrient medium and moderate light intensity, temperature and pH are required [3,10,24]. The second refers to a red, non-motile resting stage, in which cell division stops and chlorophyll levels do not fluctuate, resulting in a continuous increase of astaxanthin content and cellular dry weight. The inhibition of cell proliferation and, thus, the accumulation of astaxanthin are triggered, when microalgal cells experience nutrient starvation. Further adverse environmental conditions involve high light intensity, high temperature and salt stress [9,39,57].