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Technical-economic Prefeasibility Study of Astaxanthin Production System from *H. pluvial* Microalgae in Colombia

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Abstract

Background: Nowadays, microalgae has been considered as source of valuable products such as astaxanthin, which is a carotenoid with great commercial potential as antioxidant widely used in many industries such as pharmaceutical, cosmetics and health supplement. **Objectives:** This work was focused on technical-economic pre-feasibility study of hybrid system for cultivation, harvesting and extraction of astaxanthin from *H. pluvialis* microalgae in five Colombian cities (Barranquilla, Cartagena, Santa Marta, Barrancabermeja and Cúcuta). **Methods/Analysis:** A hybrid system was purposed based on flat panel + open pond Photo Bioreactor (PBR), in which cell growth is inhibited by increasing radiation. Additional stages as centrifugation, filtration, and drying, milling and supercritical extraction were also implemented. An economic prefeasibility study was applied in order to determine the suitability of locations in terms of NPV, IRR and PP. **Findings:** It was found that the most feasible location for astaxanthin production is Santa Marta with NPV, IRR and PP of € 5,529,203, 50% and 1.9 years, respectively. **Novelty/Improvement:** These results suggested that astaxanthin can satisfy national demand of antioxidants by producing it from *H. pluvialis* microalgae.

Keywords: Antioxidant, Astaxanthin, *H. pluvialis,* Microalgae, Technical-economic Prefeasibility

1. Introduction

Microalgae are sunlight-driven cell factories that convert carbon dioxide into potential high-value products in food, energy, cosmetic and pharmaceutical industries[1], which have been proposed an alternative lutein source. This communication determined the contents of free lutein and lutein ester of two marigold flowers (Tagetes erecta and Tagetes patula[2]. Microalgae exhibit higher photosynthetic efficiencies, higher yields and growth rates, fewer land cultivation requirements and they are capable of growing even in salty and polluted water, hence, large-scale *microalgal* production should not diminish environmental resources[3–5]. The nutritional composition of microalgae mainly consists of carbohydrate, proteins, lipids and trace elements[6], which varies with algae strain and the cultivation conditions[7]. In general, microalgae cells comprised of 20–40% lipids, 30–50% proteins, 0–20% carbohydrates, 0– 5% nucleic acids[7].

Many high-value contents of algae cell, including antioxidants, can be regarded as economically valuable co-products due to favourability economic of cultivation system[9,10]. Astaxanthin has attracted attention as a nutritional supplement, being an inhibitor of lipid peroxida-

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tion, reducing gastric inflammation, neuroprotective and immunomodulation potential[11]. *Haematococcus pluvialis* microalgae is able to synthetize and accumulate astaxanthin in 2-5 % of algal dry weight under different stress such as temperature, light, nutrient concentration, pH and inhibitors[12]. Currently, natural astaxanthin has a market of 300 t/year with an approximate cost of 1.2 million dollars, while synthetic astaxanthin produced from petrochemical sources constitutes more than 200 million annually and exhibits a sale price of 2,000 USD/ kg pure astaxanthin[13]. Actually, there are not Colombian industries for producing this metabolite and 150 t/year of astaxanthin have been exported from United States, France, Guatemala, Honduras, Mexico and Panama. In this work, technical-economic pre-feasibility study of hybrid system for cultivation, harvesting and extraction of astaxanthin from *H. pluvialis* microalgae was carried out in order to determine viability of this process in five Colombian cities.

2. Materials and Methods

2.1 Evaluation of Astaxanthin Market Size

To determine the size of the national market of astaxanthin, three databases were analyzed (National Administrative Department of Statistics, International Trade Data Bank and B2B Quimi Net platform).

2.2 Simulation

The simulation of biomass growth was performed in EnAlgae platform, which required information about climatic conditions (solar radiation, temperature, precipitation and evaporation) provided by Institute of Hydrology, Meteorology and Environmental Studies (IDEAM) and National Aeronautics and Space Administration (NASA). Five Colombian cities were selected to evaluate plant location: Barrancabermeja, Santander (7° 04'03"N, 73 ° 50'50" W), Barranquilla, Atlántico (10° 57' 50"N, 74° 47'47" W), Cartagena, Bolívar (10° 25'25"N, 75° 31'31" W), Cúcuta, Norte de Santander (7° 54'27"N, 72 ° 30'17" W) and Santa Marta, Magdalena (11° 14'10"N, 74° 12'06" W).

2.2.1 Scenarios

The effect of natural and artificial light was studied through two scenarios:

- Cultivation system using solar radiation (scenario 1).
- Cultivation system assisted by LED artificial light (scenario 2).

2.2.2 Software Modification

The EnAlgae platform provides three software (Open Pond, Flat Panel and tubular PBR) used to calculate production cost and biomass concentration. The model of photoautotrophic growth of microalgae was used. Biomass productivity is determined from glucose production (G; kg/month), monthly global radiation (RAD; J/cm^2 month), energy content of glucose (E_{gluc}; kJ/g) and a conversion factor for photosynthesis efficiency (CF_{LG}). This model also considers inhibitory factors of growth as suboptimal temperatures (T_f), availability or absence of CO_2 from combustion gas (CO_{2f}) and the use of dig estate instead of mineral fertilizers (Dig_f). Therefore, glucose production is calculated by Equation 1.

$$GP = RAD * PBRsurf * \frac{1}{100000} * \frac{1000}{E_{gluc}} * CF_{LG} * T_f * CO_{2f} * Dig_f \quad (1)$$

Then, dry biomass is determined from GP using Equation (2).

$$Biomass_{prod} = GP / \left(GF_{carbohydrates} * \%_{carbohydrates}\right) + (GF_{lipids} * \%_{lipids}) + (GF_{proteins} * \%_{proteins}) + (GF_{ashes} * \%_{ashes}) \quad (2)$$

The production downtime factor (CPF_{ashes}) due to accidents and the need for cleaning during cultivation is incorporated to convert the potential of biomass to real production.

$$Biomass_{real} = Biomass_{prod} * CPF_{ashes} \quad (3)$$

$$CPF_{ashes} = \left(365 - N_c * DT_c\right) / 365 \quad (4)$$

where, N_c is the number of accidents and/or cleaning events and DT_c is downtime in days due per accident and/or event.

For producing and extracting astaxanthin, a hybrid system was purposed. This system is based on the following configuration: flat panel + open pond and tubular + open pond. Additional stages were implemented as filtration, dehydration, cell disruption and supercritical extraction. Tables 1 and 2 summarize main parameters for flat panel and open pond reactors, respectively.

Table 1. Main parameters for flat panel reactor

Parameter	Value	Unit
Spacing between plates	0.03	m
Volume/Surface ratio	0.06	
Panel height	1.54	
Fence width	10	
Spacing between fences	0.77	
Surface of PBR(s)	1000	m^2
Total volume of PBR	60	m^3
Time for cleaning	4	Period/ year
Culture downtime due to cleaning	7	Days
Production downtime due to cleaning	14	
Biomass concentration inside PBR	2.1	kg ds / m^3
Percentage of dried matter after harvesting	150	
Recovery of algae biomass	0.95	%
Yield of biomass recovery from centrifugation	0.98	
Yield of biomass recovery from milling	1.00	
Yield of biomass recovery from drying	0.98	
Yield of extraction	0.97	

Table 2. Main parameters for open pond reactor

Parameter	Value	Unit
Depth of water	0.35	m
PBR Surface	1000	m^2
Pond volume	350	m^3
Photosynthetic efficiency	0.015	%
Biomass concentration	0.3	kg / m^3
Electricity consumed by pumping air	7.3	kWh/m^3, month
Electricity consumed by mixing	3.65	
Electricity consumed by heating	0.73	
Electricity consumed by centrifuge	1.25	kWh/m^3
Water recovery after centrifugation	0.9	%
CO_2 consumption efficiency	0.5	

2.3 Financial Statement Analysis

To perform financial statement analysis, both Fixed Capital Investment (FCI) and Operating Costs (COM) were considered. The FCI includes equipment costs and fixed capital costs. Information related to equipment and accessories costs were obtained from national and international manufacturer's quotations. On the other hand, the COM includes Raw Material Cost (C_{RM}), Labor Cost (C_{OL}), Utilities Cost (C_{UT}) and waste Management Cost (C_{WT}). The costs of utilities in the five Colombian cities were obtained from local energy and water providers. The amount of raw material, waste and product as well as utilities were quantified by mass and energy balances.

2.3.1 Economic Evaluation

In order to evaluate the feasibility of the plant location, Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period (PP) indicators were calculated. The Colombian city was selected according to these indicators considering positive NPV, IRR higher than interest of opportunity and PP less than useful life of the project.

3. Results and Discussion

3.1 Astaxanthin Market Size

Figure 1 shows importations of astaxanthin during the last 12 years. It was found that 188 t/year of this product have been imported during the last 5 years. In addition, there was not data related to astaxanthin production in Colombia. Hence, the market of this carotenoid in Colombia suggested that an industrial plant for producing antioxidants from microalgae is viable.

3.2 Simulation

3.2.1 Scenarios

After performing simulation on EnAlgae Platform for both scenarios, it was found that scenario 1 (solar radiation) exhibited an initial investment of € 1,814,580 and scenario 2 (LED lights) required an initial investment of € 1,953,580. However, operating cost showed significant differences between these sources of light.

Electricity represents 84% of the total operating cost, which is equivalent to € 292,583/year as shown Figure 2.

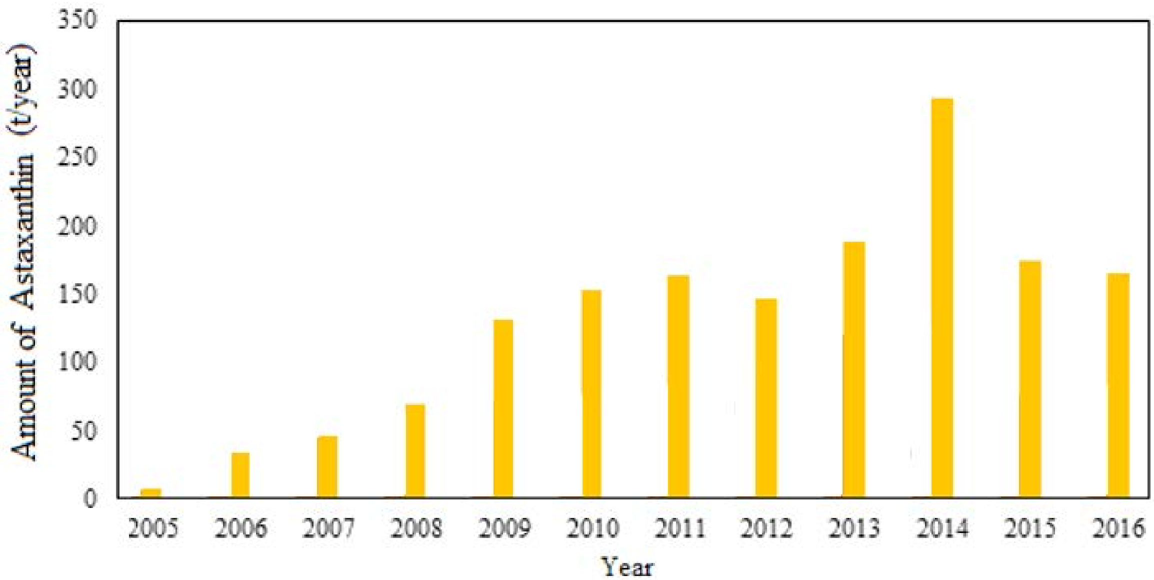

Figure 1. Imports of astaxanthin in the last 12 years.

When LED lights were implemented during microalgae cultivation, this cost increased by 44% (€ 378,506) as presented in Figure 3. Therefore, scenario 1 was selected because it provided similar production rate with lower operating cost in comparison to scenario 2.

The results obtained from EnAlgae simulator indicated the difference between biomass production and astaxanthin extraction using two types of reactors (flat panel and tubular) as shown in Figure 4[14] and Christenson and Sims[15] cell density and productivity is 2.1 g/L and 0.041 kg/Ha for flat panel and 1.7 g/L and 0.064 Kg/Ha for tubular. It was found that 12 kg astaxanthin/month (167 kg/year) and 17 kg astaxanthin/month (210 kg/year) is produced in a flat panel and tubular PBR, respectively. These results suggested that tubular reactors are not suitable to implement them in astaxanthin production process due to its lower productivity of biomass and carotenoids in comparison to flat panel.

3.2.2 Software Modification

Figure 5 shows the astaxanthin production process based on cultivation, harvesting and extraction. To provide suitable conditions for microalgae growth, fresh

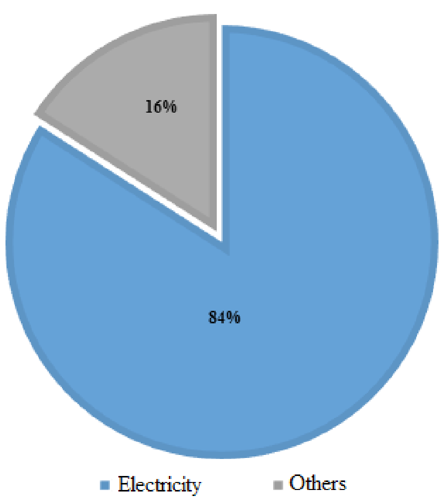

Figure 2. Annual operating cost without LED light.

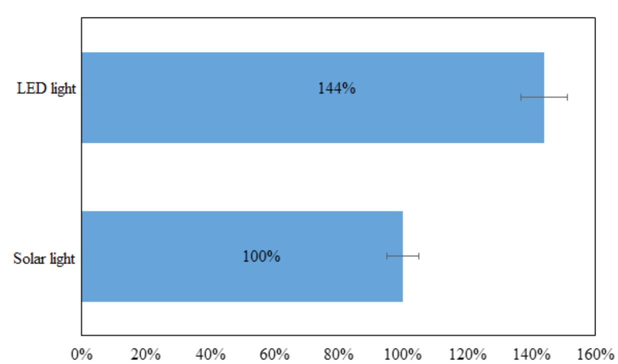

Figure 3. Effect of light source on operating cost.

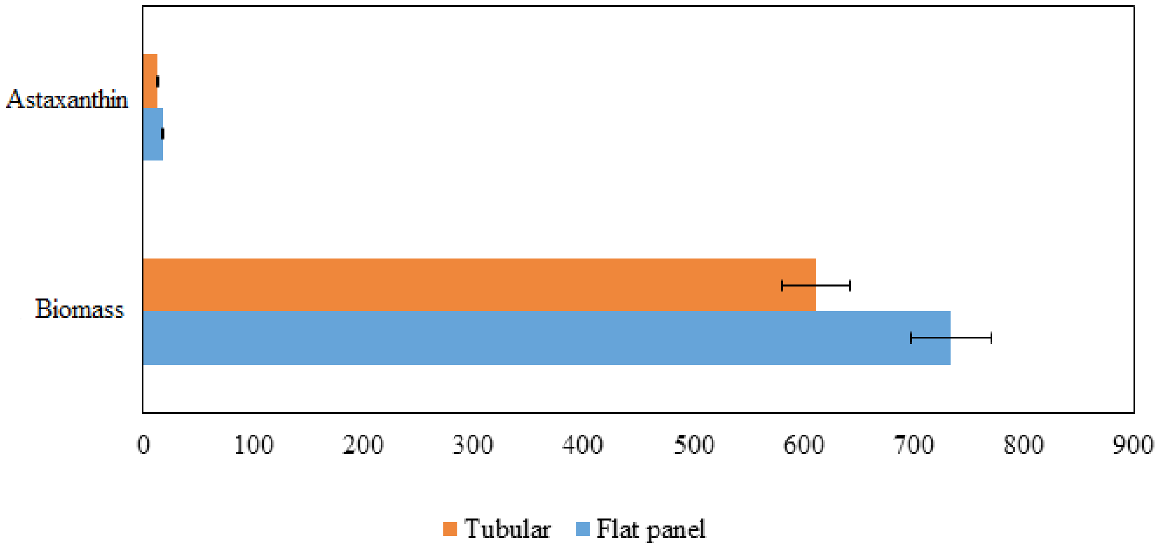

Figure 4. Monthly production of biomass and astaxanthin from *H. pluvialis* in flat panel and tubular PBR.

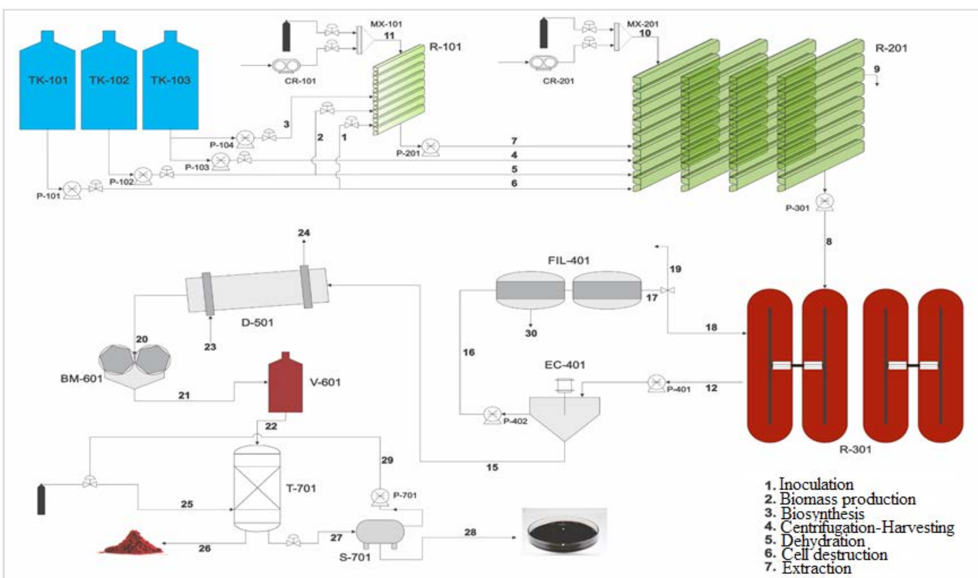

Figure 5. Process flow diagram for production and extraction of astaxanthin.

water (TK-101), micronutrients (TK-103) and macronutrients (TK-102) are sent to inoculator (R-101) and flat panel reactor during 20 days. Biosynthesis of astaxanthin takes place in open pond reactor (R-301), where microalgae is stressed by radiation increments. Then, it passes through centrifugation and drying. The dried biomass is milled (BM-601) for achieving cell disruption and sent to supercritical extraction. The extract flows to separator (S-701) where CO_2 is removed from astaxanthin. The product is commercialized at 5%, 10% and 15% of concentration.

3.3 Financial Statement Analysis

The financial statement analysis was performed using synthetic medium for *H. Pluvialis*. For astaxanthin production, the cost of waste treatment (C_{WT}) is € 586/year. Minimum wage in Colombia is € 237/month according to the decree No. 2269 of December 2017. Professional

Table 3. Process equipment cost

Equipment	Value [€]
Reactor	460,150
Storage tank	20,000
Heat exchanger	218,959
Degassing tank	179,148
Control instruments	159,243
Infrastructure phase 1	378,202
Infrastructure phase 2	65,941
Storage tank	10,000
Dryer	27,000
Ball mill	50,000
LED lights	517,539
Centrifuge	25,087
Filter	3,850
Supercritical extraction	267,000
TOTAL	2,382,119

(H_Q) and technical (L_Q) workforce cost is € 4.3/hour and € 2.8/hour, respectively. Hence, labor cost (C_{OL}) is € 11,248/year. Fixed capital investment for equipment and utilities cost are summarized in Tables 3,4.

Table 5 summarizes fixed capital investment, cost of raw material and cost of utilities for astaxanthin production process. The FCI is variable for this product due to it depends on equipment and land costs, which vary according to the city where industrial plant is located. The cost of raw material for astaxanthin did not exhibit significant variations because of the main contribution is due to synthetic medium costs. The product is not commercialized with 100% purity; hence, olive oil was used as dissolvent.

3.4 Economic Evaluation

Economic evaluation was performed using NPV, IRR and PP as indicators for astaxanthin production process. As is shown in Figures 6, 7, Santa Marta is the most viable for locating astaxanthin plant with NPV of € 5,529,203, PP of 1.9 years and IRR of 50%, which is higher than interest of opportunity (12%)reported by Bank of the Republic. To select product presentation for sale, it was considered the break-even analysis and sale prices in global market. The sales price of astaxanthin in global market varies between 2,580- 6,020 € /kg, hence a minimum sale price of € 1,537/kg at product concentration of 5%is recommended.

4. Conclusion

This research attempted to evaluate the feasibility for producing astaxanthin in five cities of Colombia (Barranquilla, Cartagena, Santa Marta, Barrancabermeja and Cucuta). Results suggested that national market of carotenoids exhibits high demand but no offer, hence,

Table 4. Cost of utilities and land in Colombian cities

City	Electricity[€/ kW/h]	Water [€/m^3]	Land [€/ha]
Barrancabermeja	0.19	0.92	208,467
Barranquilla	0.15	1	61,507
Cartagena	0.15	0.73	127,325
Cúcuta	0.14	0.96	481,078
Santa Marta	0.15	0.69	117,607

Table 5. FCI, C_{RM} and C_{UT} for astaxanth in production process

City	FCI[€]	C_{RM}[€]	C_{UT} 5% [€]	C_{UT} 15% [€]	C_{UT} 20% [€]
Barrancabermeja	1,987,202	5,703,732	336,491	361,141	333,020
Barranquilla	1,918,142	5,703,732	273,023	265,945	263,585
Cartagena	1,917,180	5,703,317	271,084	264,224	261,938
Cúcuta	2,067,796	5,705,215	278,449	268,370	265,010
Santa Marta	1,923,551	5,704,232	276,612	268,201	265,397

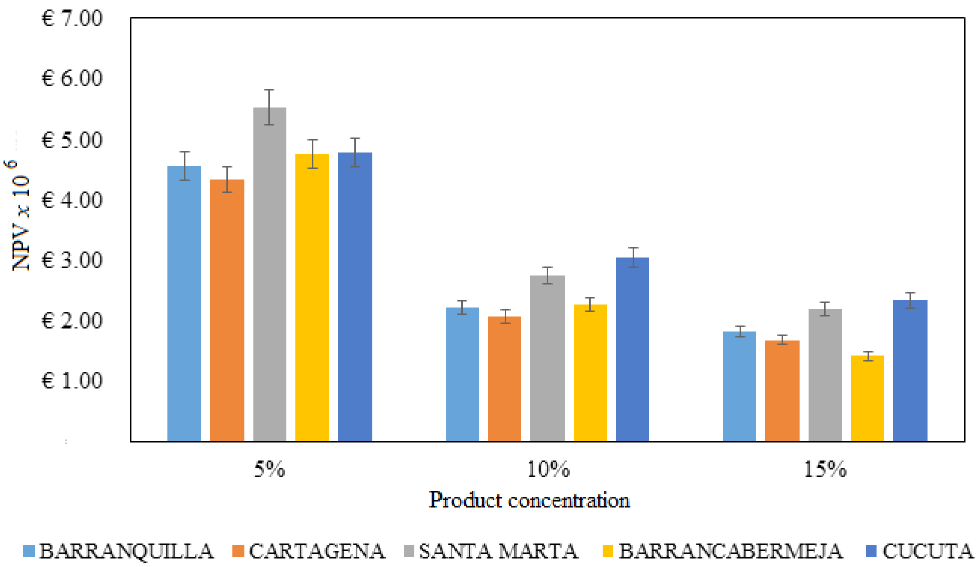

Figure 6. Net present value for astaxanthin production at three different product concentrations.

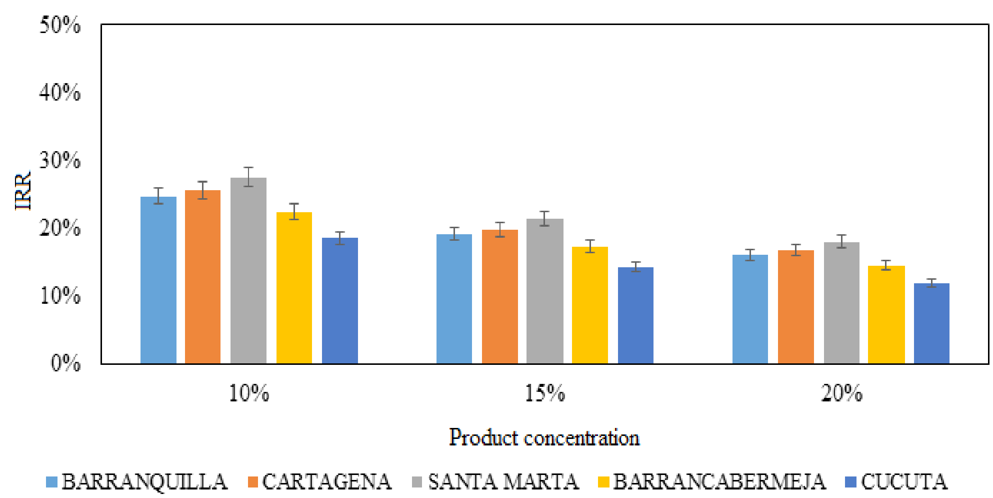

Figure 7. Internal rate of return for astaxanthin production at three different product concentration.

astaxanthin production in Colombia attracts great attention for locating industrial plants. The hybrid system that produces highest biomass amount is flat panel + open pond PBR with biomass/year. Santa Marta was selected as best city to locate the plant with NPV of € 5,529,203, PP of 1.9 years and IRR of 50% for astaxanthin.

5. Acknowledgement

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