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Economic Evaluation and Techno-Economic Sensibility Analysis of a Mass Integrated Shrimp Biorefinery in North Colombia

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Abstract: Huge amounts of wastes are generated during shrimp processing, representing approximately 65% of the initial shrimp weight, which can become an environmental problem when accumulated. Residues such as shrimp shells can be processed to obtain value-added products such as chitin, chitosan, astaxanthin, and a nitrogenous extract under the biorefinery concept. In this work, the economic evaluation and the techno-economic sensibility analysis for a mass integrated biorefinery based on shrimp were developed to determine the economic feasibility of the project and to identify the critical techno-economic variables that affect the profitability of the process. The results showed that a biorefinery for the annual processing of 4,113.09 tons of fresh shrimp in Colombia is profitable, with a return on investment percentage (%ROI) equal to 65.88% and a net present value (NPV) of 10.40 MM USD. The process supports decreases of up to 28% in capacity of production and increases of 12% and 11% in the cost of raw materials and variable operating costs without incurring losses, respectively. However, the decrease over 500 USD/t in the shrimp meat selling price is not supported, thus it is mainly recommended to increase the selling price of this product.

Keywords: economic evaluation; techno-economic sensibility; biorefinery; shrimp; chitin; chitosan; astaxanthin

1. Introduction

Huge amount of wastes are generated during shrimp processing, representing approximately 65% of the initial shrimp weight [1] including shrimp heads and exoskeleton. Shrimp represents approximately 45% of the total seafood consumed worldwide [2], therefore, the shrimp farming and processing industry is the largest fishing industry in the world. Shrimp is widely consumed for its high nutritional value, due to being a food rich in protein [3]. The current production of shrimp is estimated to be close to reaching 5.03 million tons per year [4] and demand is expected to continue growing in the coming years.

It is known that shrimp shells are composed of chitin, protein, minerals, and carotenoids [5]. Chitin is a type of biopolymer, the second most available in nature [6], considered an important material due to its properties, such as biodegradability, non-toxicity, thermal stability, immunogenicity, and biocompatibility [7]. Chitin and its derivatives such as chitosan are widely used in papermaking [8], pharmaceutical [9], and cosmetics [10] industry, wastewater treatment, and agriculture [11]. On the other hand, carotenoids are an important type of organic pigments that have been used as nutritional supplements[12]. Astaxanthin is a type of carotenoid extracted from the shrimp exoskeleton and has been extensively studied to have antitumor and anti-inflammatory properties [13] and is commonly used as a food additive for fish [14].

The design of a shrimp-based biorefinery for shrimp meat, chitin, chitosan, astaxanthin, and nitrogenous extract production is an option to take advantage of the residues from shrimp processing and thus reduce the environmental impacts generated by the accumulation of these wastes. Sustainability is an innate characteristic of biorefineries for having a biological origin [15], a biorefinery should include all the sustainability pillars including the economic factor [16]. Therefore, including optimization techniques such as mass integration in the design of biorefineries minimizes the fresh material consumption and waste discharge and reduces costs [17] allowing the process to be more sustainable and with better economic performance. Studies carried out on algae-based biorefineries for biofuel production have shown that wastewater recovery has a positive influence on the economic indicators of the process. For an attached growth algal biorefinery mass integrated was found that the minimum selling price of the fuel can be reduced up to 150% [18] compared to the non-integrated case without generating losses. While for a process optimized for the production of the biojet-fuel intermediate from biomass, reductions in total annual costs of 89.76% were shown [19].

For a shrimp-based mass integrated biorefinery, there is no information indicating its economic feasibility, hence, it is necessary to perform an economic evaluation of the process considering that energy and equipment costs increase by different percentages compared to the processing or production scale [20]. Several studies have evaluated different configurations of biorefineries from an economic point of view considering different economic indicators such as net present value, return on investment percentage, and payback period, including an African palm biorefinery [21] and a lignocellulosic multi feedstock biorefinery [22]. The results showed that both biorefineries were profitable, generated profits before ten years, and are highly sensitive to variations in techno-economic variables. In this work, the economic evaluation for a mass integrated biorefinery based on shrimp is carried out to determine the profitability of the project through the estimation of economic indicators. Also, the economic sensibility analysis is developed to analyze the process performance to variations in the capacity of production, raw material costs, variable operating costs, and selling price of the products.

2. Materials and Methods

2.1. Process Description

The mass integrated biorefinery based on shrimps includes four steps: meat production from fresh shrimp processing, chitin extraction, chitosan production, and astaxanthin extraction from shrimp shells processing. The process diagram is shown in Figure 1.

Fresh shrimps are fed to the meat production unit where are initially washed at low temperatures with sodium metabisulfite to remove the impurities and prevent shrimp melanosis [23] and sorted to discard the stained and damaged shrimp. Subsequently, the shrimp heads and shell are removed and the shrimp meat is obtained. The shrimp exoskeletons are sent to the chitin extraction unit to processed for recovery of value-added products.

The shrimp shells are first pre-treated to reduce in size to a pore size of 0.5 mm [5]. The astaxanthin is extracted using ethanol [24] in the depigmentation stage; the residual-pigment mixture is moved toward the astaxanthin extraction step while the shell powder goes to a demineralization process. In the demineralization unit, removed the minerals present in the shrimp shells by hydrochloric acid addition to preventing the chitin hydrolysis [25]. After the demineralization reaction, the mainstream is neutralized with NaOH and washed to bring the stream to a neutral pH [26]. Wastewater from the washing that contains large amounts of NaOH is mixed with fresh sources and sent back to the neutralization and washing stages. Next, the proteins are separated from shrimp shells by the addition of sodium hydroxide to extract the chitin [27]. A nitrogenous extract is obtained of this stage as a by-product which can be used in agriculture as fertilizer. The chitin extracted is neutralized with HCl and washed to ensure the neutral pH [26]. The wastewater from the chitin washing unit is also recycled to the neutralization and washing units.

Half of the chitin was obtained and dried to isolated this by-product and the rest is processed in the chitosan production unit. The chitin is transformed into chitosan by the acetyl group removal [28] in a deacetylation stage where elevated temperatures and a high concentration of NaOH are required. Then, the chitosan is sent to neutralization with HCl and washing; the wastewater rich in hydrochloric acid from this washing unit is reused in these same stages. Finally, the chitosan is dried in an oven at 100°C [29]. The reuse of wastewater from washing units minimized freshwater, NaOH, and HCl consumption.

On the other hand, in the astaxanthin obtaining step, the residual-pigment mixture is subject to a second depigmentation where acetone is added and the entire astaxanthin is extracted [1] and purified.

Table 1 lists mass flowrates for the main process streams and operational conditions of this process. For a processing capacity of 4,113.09 t/y according to the farmed shrimp production rate in north Colombia in 2018 [30] was reported a production rate of 2,417.66 t/y shrimp meat, 35.13 t/y chitin, 29.21 t/y chitosan, 99.55 t/y nitrogenous extract, and 1t/y astaxanthin.

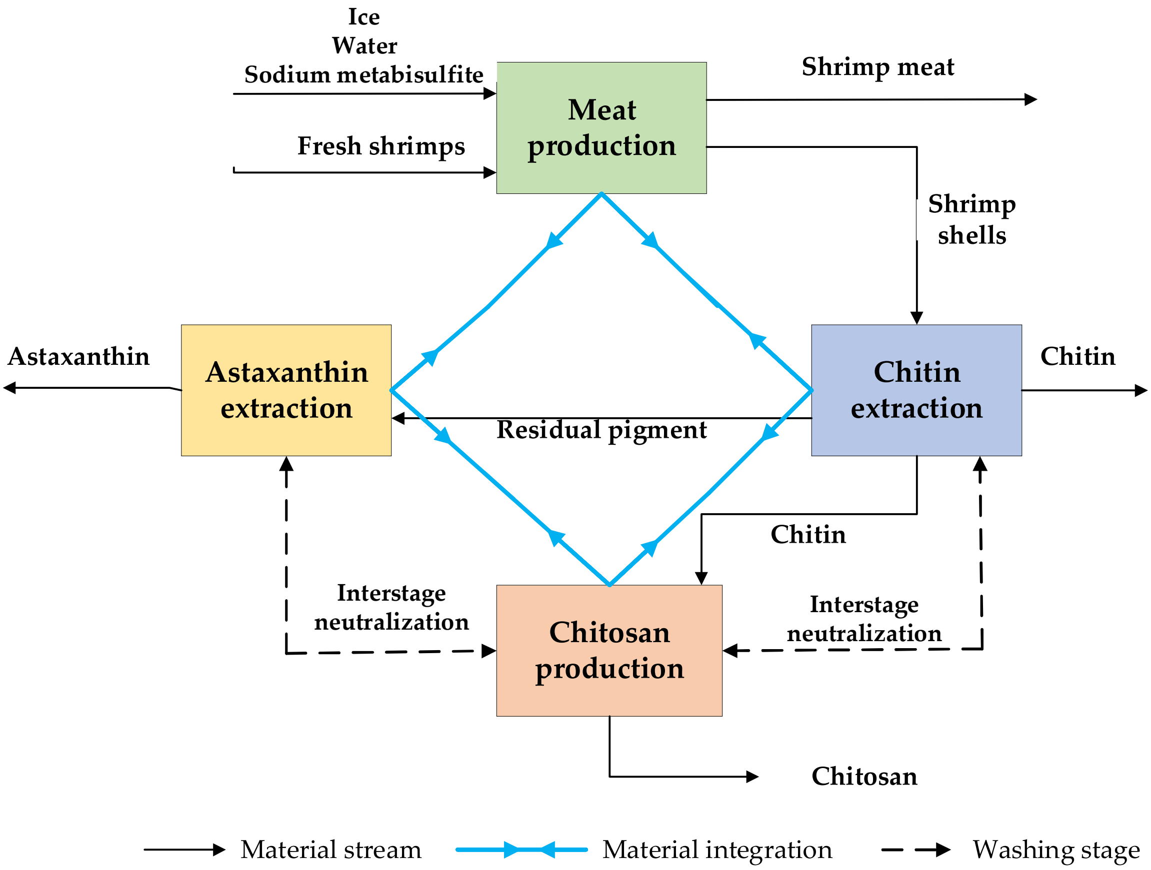

Figure 1. Process diagram of a mass integrated biorefinery based on shrimp

Table 1. Main process streams for mass integrated biorefinery based on shrimp

Streams	Fresh Shrimp	Shells	Meat	Astaxanthin	Nitrogenous extract	Chitin	Chitosan
Temperature (K)	286.38		282.15	298.15	363.15	373.15	298.16
Pressure (kPa)	101.32	101.32	101.32	101.32	101.32	101.32	101.32
			Components mass flow (kg/h)				
L-Alanine	16.64	1.76	9.75	0.00	1.76	0.00	0.00

L-Glutamic-acid	28.68	3.04	16.81	0.00	3.04	0.00	0.00
L-phenylalanine	10.80	1.15	6.33	0.00	1.15	0.00	0.00
Methionine	9.70	1.03	5.68	0.00	1.03	0.00	0.00
Lysine	31.35	3.32	18.37	0.00	3.32	0.00	0.00
Calcium Carbonate	8.31	1.40	2.83	0.00	0.00	0.00	0.00
Calcium phosphate	20.86	3.52	7.11	0.00	0.00	0.00	0.00
Sodium carbonate	4.24	0.72	1.44	0.00	0.00	0.00	0.00
Magnesium carbonate	2.45	0.41	0.83	0.00	0.00	0.00	0.00
D-N-acetylglucosamine	32.00	8.20	0.00	0.00	0.00	4.01	0.00
Methyl-palmitate	57.73	14.36	1.67	0.00	0.00	0.00	0.00
Astaxanthin	0.44	0.11	0.00	0.11	0.00	0.00	0.00
Water	246.01	9.91	204.97	0.00	443.27	0.00	0.09
Carbon dioxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Magnesium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Calcium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hydrogen chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orthophosphoric- acid	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ethanol	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium hydroxide	0.00	0.00	0.00	0.00	6.88	0.00	0.00
Sodium chloride	0.00	0.00	0.00	0.00	0.00	0.00	0.00
hydroxypropylammoniun	0.00	0.00	0.00	0.00	0.00	0.00	3.25
Sodium acetate	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium metabisulfite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium hypochlorite	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Acetone	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	469.21	48.93	275.80	0.11	460.44	4.01	3.33

2.2. Economic evaluation

The economic analysis is a tool to evaluate the profitability of a project and establish if a process is feasible or not under economic criteria [31]. Primary costs are calculated as Total Capital Investment (TCI) and Operating Costs (OC).

The total capital investment is calculated as indicated equation 1 by three terms: Fixed Capital Investment (FCI) refers to the money needed to pay for equipment, piping, electrical installations, land, civil structures, legal costs, and control systems, Working Capital Investment (WCI) is the money necessary to pay for operating costs before the sale of products begins and Start-Up Costs (SUC) that include legal, publicity and employee training costs. While, operating costs are estimated as the money needed to maintain the plant in operation once production starts and includes Direct Production Costs (DPC), Fixed Charges (FCH), Plant Overhead (POH), and General Expenses (GE) [32]as shown equation 2.

$$TCI = FCI + WCI + SUC \quad (1)$$

$$OC = DPC + FCH + POH + GE \quad (2)$$

According to equation 3, the On-Stream efficiency was calculated as the relation between production capacity on BEP (m_{BEP}) and the maximum production capacity (m_{max}). Economic indicators such as gross profit (depreciation not included) (GP), gross profit (depreciation included) (DGP), profit after taxes (PAT), normalized variable operating costs (NVOC), economic potentials

(EP1, EP2, EP3), cumulative cash flow (CCF), payback period (PBP), the return of investment percentage (ROI%) and net present value (NPV) were calculated by equations 4 - 13 [32].

$$\eta_{On-stream}^{BEP} = \frac{m_{BEP}}{m_{max}} \quad (3)$$

$$DGP = \sum_i m_i C_i^v - TAC \quad (4)$$

$$PAT = DGP(1 - itr) \quad (5)$$

$$NVOC = \frac{AOC - FCH}{m_{RM}} \quad (6)$$

$$EP_1 = \sum_i m_i C_i{}^v - \sum_i m_j\, C_j{}^{RM} \quad (7)$$

$$EP_2 = \sum_i m_i C_i{}^v - \sum_i m_j\, C_j{}^{RM} - U \quad (8)$$

$$EP_3 = \sum_i m_i C_i{}^v - AOC \quad (9)$$

$$CCF = \frac{\sum_i m_i C_i^v - AOC}{TCI} \quad (10)$$

$$PBP = \frac{FCI}{PAT} \quad (11)$$

$$\%ROI = \frac{PAT}{TCI} x100 \quad (12)$$

$$NPV = \sum_n ACF_n\,(1 + i)^{-n} \quad (13)$$

Where $m_i C_i^v$ is the flowrate and selling price of product i, TAC is the total annualized cost, itr is the income tax rate, m_{RM} is the raw material flowrate, $m_j C_j^{RM}$ is the flowrate and cost of raw material, U are the utilities, ACF_n is the net income for the nth year and i the interest [33]

3. Results

3.1. Economic evaluation

The economic assessment for the mass integrated biorefinery based on shrimp was developed considering the assumptions presented in table 2. The cost of raw materials was estimated by vendor quotes from the Alibaba website (www.alibaba.com) [34]. The product selling price was also defined based on the information supplied by the Alibaba website as shown in table 3.

Table 2. Economic assumptions for the mass integrated biorefinery bases on shrimp

Assumptions	Value
Processing capacity (t/y)	4,113.09
Main product flowrate (t/y)	2,417.66

Raw material cost (USD/t)	6,724.27
Plant life (y)	15
Salvage value	10% of depreciable FCI
Construction time of the plant (y)	3
Location	Colombia
Tax rate	39%
Discount rate	8%
Subsidies (USD/y)	0
Type of process	New and unproven
Process control	Digital
Project type	Plant on non-built land
Percentage of contingency	20%
Salary per operator (USD/h)	30
Utilities	Electricity, steam, water
Process fluids	Solid-liquid-gas

Table 3. The selling price of products

Product	Selling price (USD/t)
Shrimp meat	16,500
Chitin	17,000
Chitosan	35,000
Nitrogenous extract	1,000
Astaxanthin	40,000

The total capital investment for the mass integrated biorefinery based on shrimp is shown in table 4. The costs associated with the purchase of the equipment were determined using the Process Economics Analyzer tool from the Aspen Plus® software. The equipment represents the highest costs compared to other factors affecting the FCI. Table 5 presents the annualized operating costs, the raw materials consumed in the process were fresh shrimp, sodium metabisulfite, acetone, sodium hydrochloride hydroxide. The utilities cost used was estimated according to the actual value in Colombia.

Table 4. Total capital investment for the mass integrated biorefinery based on shrimp

Cost of capital investment	Total (USD)
Delivered purchased equipment cost	713,460.00
Purchased equipment (installation)	142,692.00
Instrumentation (installed)	57,076.80
Piping (installed)	142,692.00
Electrical (installed)	92,749.80
Buildings (including services)	285,384.00
Services facilities (installed)	214,038.00
Total DFCI	1,648,092.60
Land	42,807.60
Yard improvements	285,384.00
Engineering and supervision	228,307.20
Equipment (R+D)	71,346.00
Construction expenses	242,576.40
Legal expenses	7,134.60
Contractors' fee	49,942.20
Contingency	142,692.00
Total FCI	1,070,190.00
Fixed capital investment (FCI)	2,718,282.60

Working capital (WC)	1,359,141.30
Start up (SU)	271,828.26
Total Capital Investment (TCI)	4,349,252.16

Table 5. The annual operating cost for the mass integrated biorefinery based on shrimp

Operating costs	Total (USD/y)
Raw materials	27,657,569.90
Utilities (U)	218,981.17
Maintenance and repairs	135,914.13
Operating supplies	20,387.12
Operating labor	561,600.00
Direct supervision and clerical labor	84,240.00
Laboratory charges	56,160.00
Patents and royalties	27,182.83
Direct production cost (DPC)	28,762,035.14
Depreciation	187,283.25
Local taxes	81,548.48
Insurance	27,182.83
Interest/rent	43,492.52
Fixed charges (FCH)	330,588.83
Plant overhead (POH)	336,960.00
Total Manufacturing Cost	29,429,583.97
General expenses (GE)	7,357,395.99
Annualized Total Operating costs (AOC)	36,786,979.96

3.2. Economic indicators

The economic indicators for the mass integrated biorefinery based on shrimp are presented in table 6.

Table 6. Economic indicators for the mass integrated biorefinery based on shrimp

Economic indicator	Value	Units
Gross Profit (depreciation not included) (GP)	4.88	MM USD
Gross Profit (depreciation included) (DGP)	4.70	MM USD
Profit After taxes (PAT)	2.87	MM USD
Revenues	41.65	MM USD/y
Economic Potential 1 ($/y)	13.99	MM USD/y
Economic Potential 2 ($/y)	13.77	MM USD/y
Economic Potential 3 ($/y)	4.86	MM USD/ y
Cumulative Cash Flow	1.12	(1 /y)
Payback Period (depreciation included) (DPBP)	6.00	y
ROI	65.88	%
Net present value (NPV)	10.40	MM USD
Annual Cost/ Revenue	1.22	

3.3. Sensibility analysis

The break-even analysis is illustrated in figure 2. It can be initially observed that the process is feasible from a techno-economic point of view by operating at 100% of the installed capacity since the annual sales are higher than the annual operating costs (AOC). The break-even point is achieved by processing 1,150 tons of raw material per year, approximately 28% of the installed capacity. Therefore, the process is highly sensitive to changes in the capacity of production, which is beneficial given that the availability of fresh shrimp can be affected by external factors such as climate and market conditions. Consequently, the capacity of production can be reduced to less than half, and the process profitability is not affected.

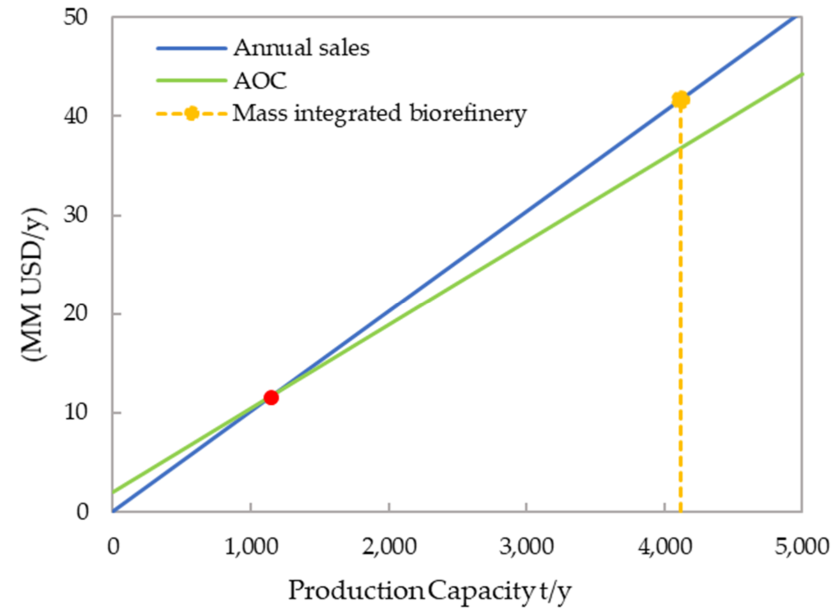

Figure 2. Break-even analysis for the mass integrated biorefinery based on shrimp

On-stream efficiency sensibility analysis for the mass integrated biorefinery based on shrimp is presented in figure 3. It can be shown that the on-stream efficiency is highly sensitive to changes in the selling price of shrimp meat, while the selling price of chitin, chitosan, nitrogenous extract, and astaxanthin does not significantly influence on the on-stream efficiency. Besides, from the figure three regions can be identified, the first where the on-stream efficiency presents a highly sensitive to the selling price; the second named transition period, in which the change in the on-stream efficiency is not pronounced allowing to greater operability to changes in the selling price and a third region, where although the selling price increases to a great extent do not cause changes in the on-stream efficiency. According to table 3, the selling price for the products is located in the second region, however, it is observed that the selling price for shrimp meat is very close to the critical value (16,000 USD/t) which can risk the profitability of the process. It was found that the selling price of shrimp meat does not support decreases higher than 500 USD/t.

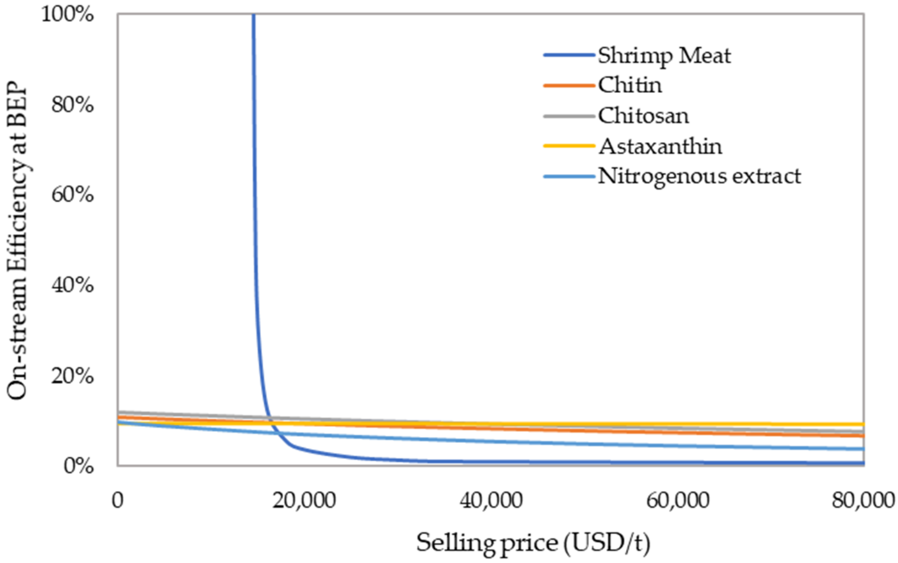

Figure 3. Effect of the selling price on on-stream efficiency

The effect of raw material costs on the process profitability was also evaluated and the results are shown in figure 4. The biorefinery describes a high sensibility to changes in raw material costs with a critical point around 7,600 USD/t, above this value the process generates economic losses. According to table 5, the current cost of raw materials is 6,724.17 USD/t which is an acceptable value because it can increase to 12% without risking the profitability of the project.

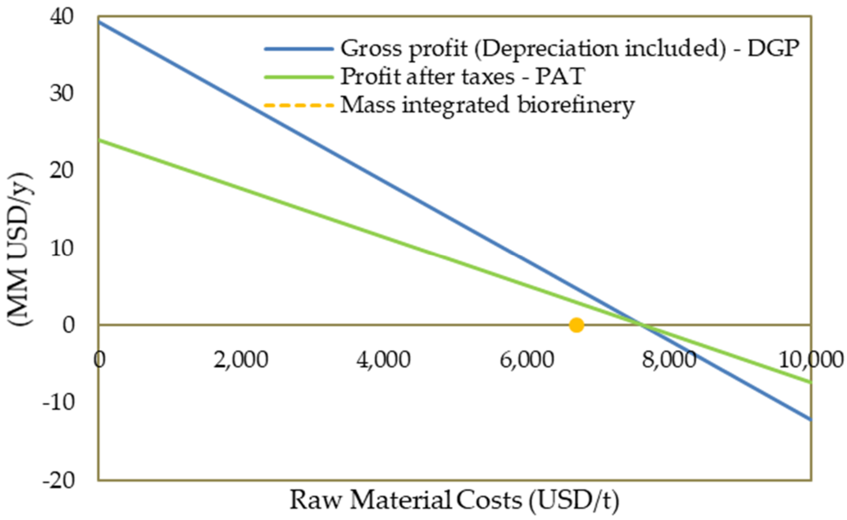

Figure 4. Effect of raw material cost on profitability

Figures 5 and 6 present the effect of variable operating costs (utilities, maintenance, repairs, labor, supervision) on the return on investment percentage and payback period, respectively. The findings showed that the NVOC achieves a critical value around 10,000 USD/t where the %ROI is null and the PBP tends to infinity. The variable operating costs for the biorefinery are approximately 11% below this value indicating that the process is safe from increases in these costs. These results are favorable considering several common problems that can affect the NVOC such as employee strikes, increased labor costs, and fuel supply. Also, it was determined that when variable operating costs are negligible the process reaches ROI greater than 500% and a PBP less than a year. Similar projects such as a chitosan production process from shrimp exoskeletons and a plant to obtain agar from red algae show a maximum return on investment of 34% [35] and 276% [26] when the NVOC is null, respectively, indicating that mass integrated biorefinery based on shrimp presents a better performance in terms of return on investment.

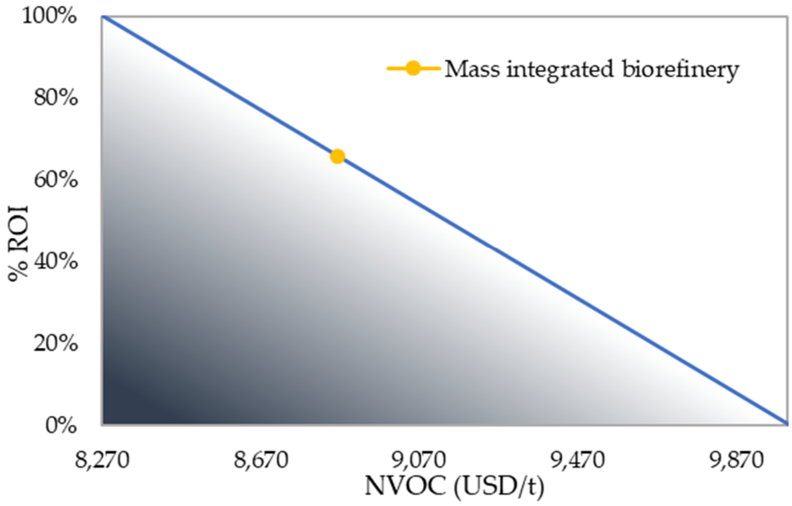

Figure 5. Effect of variable operating cost on return on investment

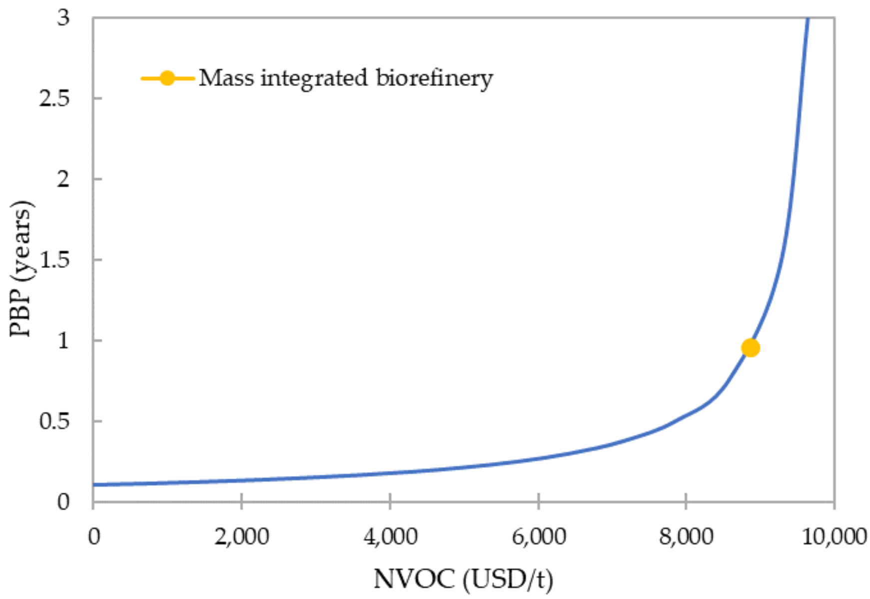

Figure 6. Effect of variable operating cost on the payback period

The variation of the net present value during the 15 years of plant life is illustrated in figure 7. The finding shows that the NPV is positive from year 7, in other words, the investment will produce a profit from this year and reaches and NPV of 10.40 MM USD by the end of the project.

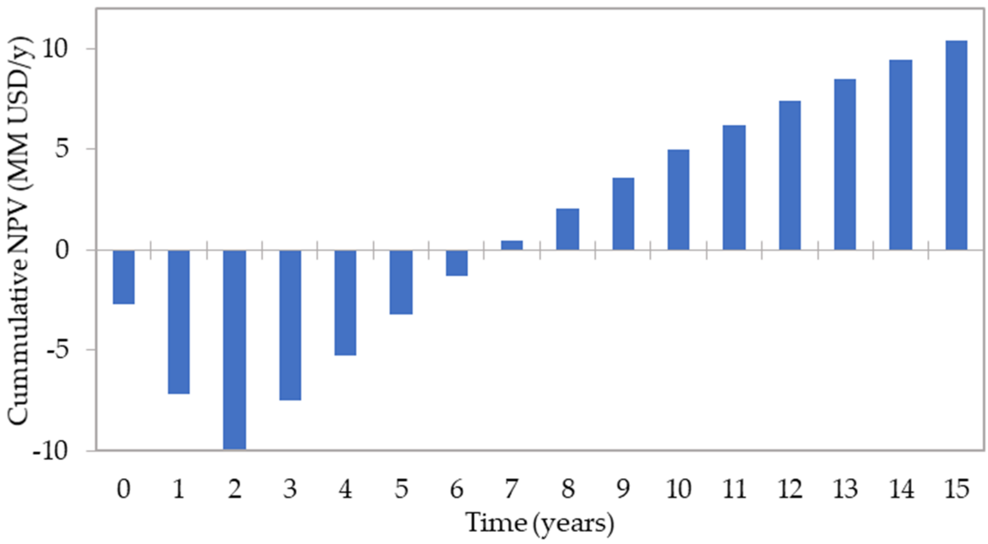

Figure 7. The net present value for the mass integrated biorefinery based on shrimp

4. Discussion

The results obtained from the economic analysis for the biorefinery indicate that the return on investment percentage (%ROI) is 65.88%, which shows the project is economically feasible, considering that projects with %ROI between 10-15% are feasible from the economic viewpoint, according to El-Halwagi [36]. Nevertheless, the cumulative cash flow calculated indicates that the initial investment is significantly high compared to the annual revenues [18], thus, according to the payback period including depreciation, 6 years are required to recover the whole investment. These results are acceptable considering that the plant life is 15 years and by the end of this time the investment is recovered; less than half of the useful period is required to recover the investment. At the end of the project, a net profit of 10.40 MMUSD is guaranteed as indicated by the net present value.

Besides, the findings show that the mass integrated biorefinery based on shrimp has a good economic performance against changes that affect their operating conditions. The process supports decreases in production capacity and increases in raw material costs and variable operating costs. However, it was found that the critical techno-economic variable is the selling price of shrimp meat; hence, it is mainly recommended to increase the price of this product not exceeding 37,000 USD/t since higher values do not represent changes in on-stream efficiency. The average selling price of shrimp meat in Colombia is around 18,510 USD/t [37]. Therefore, increases need to be made guaranteeing the competitiveness of the process in the national markets.

Comparing with the economic results for other biorefineries it was found that the return on investment percentage for a lignocellulosic multi feedstock biorefinery was 32% [22] and for a combined palm and jatropha biomass biorefinery for biodiesel and hydrogen production was 33.18% [38] which shows that the mass integrated biorefinery based on shrimp is more economically attractive. On the other hand, the net profits for the biorefinery were estimated to be up to 95% higher than the net profit obtained in a chitosan production process from shrimp exoskeleton [39] which is due to the larger number of products sold in the biorefinery. However, the chitosan production process showed a higher sensibility to changes in the cost of raw materials, production capacity, variable operating costs, and the selling price of the product [35].

The results suggest that mass integration techniques contribute to the profitability of a process by minimizing the cost of raw materials. Besides, the reduction in freshwater consumption provides environmental and social benefits; studies indicate how the same optimization techniques can reduce the generation of environmental impacts [40]. Therefore, a mass integrated biorefinery based on shrimp is considered a profitable economic activity with the potential to drive the economic and social development of northern Colombia.

5. Conclusions

The economic evaluation and techno-economic sensibility analysis for a mass integrated biorefinery shrimp-based located in Colombia for the production of shrimp meat, chitin, chitosan, nitrogenous extract, and astaxanthin were carried out to determine its feasibility and to identify the critical techno-economic variables that affect the profitability of the process. For a processing capacity of 4,113.09 t/year of fresh shrimp, the process is economically attractive, as indicated by the obtained %ROI of 65.88%, and 6 years are required to recover the whole investment. Also, it was identified that the process supports decreases of up to 28% in production capacity and increases of 12% and 11% in the cost of raw materials and variable operating costs, respectively, without incurring losses. However, the decrease over 500 USD/t in the shrimp meat selling price is not supported, thus it is mainly recommended to increase the selling price of this product. The mass integration techniques allowed a reduction in the operating costs of the process; hence, the mass integrated biorefinery based on shrimp showed a higher economic performance compared to other non-integrated biorefineries.

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