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Techno-economic Sensitivity Analysis of Large Scale Chitosan Production Process from Shrimp Shell Wastes

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Chitin is one the most abundant natural amino-polysaccharides in nature, it is found in the exoskeleton of many arthropods on earth, being the main component of these ones. Great quantities of crustaceans are processed daily for human consumption, generating big shell wastes to should be correctly treated and give them a final disposal that not bringing environmental concerns to fishing industry. There are potential uses of these shell wastes, and one of them is the extraction of chitosan from chitin present in these wastes. In this work was developed the economic evaluation and the techno-economic sensitivity analysis of the large-scale production of chitosan from shrimp shell wastes via depigmentation, demineralization, deproteinization and deacetylation of chitin, using the ethanol-based route, which employs ten units of operation, in order to analyze the behavior of the process under changes of the techno-economic environment of the process as break-even point, on-stream efficiency, raw material cost, among others. Results shows that for a processing capacity of 57,000 t/y of shell waste with a plant life of 15 y, located in North Colombia, the critical techno-economic variables were raw material costs which with an increase in 100 % of price decreases the Profit After Taxes (PAT) close to zero, product selling price and normalized variable operating costs (NVOC).

1. Introduction

Chitosan is a polymeric material composed of β-(1-4) D-glucosamine units; it is obtained by chemical o enzymatic deacetylation of the chitin which is commonly found in exoskeleton of crustaceans like crabs, lobster, shrimps, etc., (Gómez-Ríos et al., 2017). It is known as the second abundance polymer, nontoxicity, biodegradability, biocompatible nature, and low cost which makes it high potential as useful sorbent in wastewater treatment (Razmi et al., 2016). During the last decade, chitin-containing marine crustacean waste have received an increased attention since the major components of this waste are chitin, protein, flavorant, pigment and minerals (Amar Cheba et al., 2018). The production of chitosan is directly related to the fishing industry. Latin-American countries, with coasts over the Pacific Ocean, consolidate around 41 % of global exportations of shrimps; Ecuador, Argentina and Mexico are the larger producers in the region (Gómez-Ríos et al., 2017). In Colombia, shrimp cultivation is performed in places around the Pacific Ocean and the production is 2,400 t/y (Virtual Pro, 2016), which approximately 20 % of the gross weight of shrimp is discarded as waste. It is reported that approximately 6-8 million t of crustacean waste is produced worldwide every year (Gao et al., 2016). The current increase in crustacean wastes from shrimp and crab industry in the most producing countries in the world (China, Indonesia, Thailand and India) pose serious disposal problems, bioconversion of crustacean waste has been proposed as an alternative treatment (FAO, 2016). That “waste” is the raw material for the chitosan production. That process consisted in some steps of pretreatment of the raw material like washing and grinding. After, the grinded exoskeleton went to the depigmentation by ethanol, then the exoskeleton went to the demineralization stage by Hydrochloric Acid, after that, the exoskeleton went to the deproteinization stage by Sodium Hydroxide and it got became in chitin. Finally, the chitin went to deacetylation by Sodium Hydroxide

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and it got became in chitosan. In Figure 1 the block diagram of the process with the main stages is shown. Novelty of this work lays in the scaling-up of a new chitosan production process from shrimp shell wastes previously developed in lab-scale by authors and application of the methodology of techno-economic sensitivity assessment for evaluation of the effect of changes in economic flows over economic process behavior, under Colombian conditions.

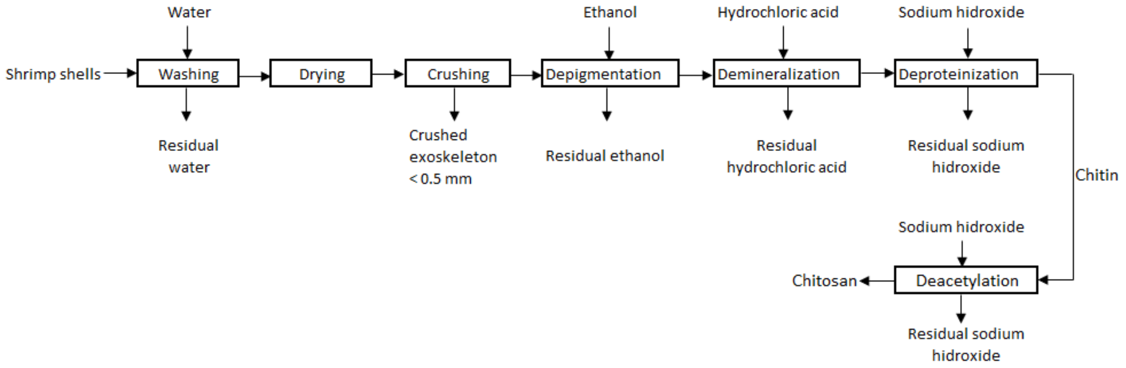


Figure 1: Block diagram with the main stages of the chitosan production process from shrimp shells

2. Techno-economic sensitivity analysis

The techno-economic sensitivity analysis was carried out based on US dollar and a plant life of 15 years as reference, and equations were taken from the analysis economic model proposer by El-Halwagi (2012). Costs of equipment, raw material price and product price were calculated through of vendors (www.alibaba.com and www.matche.com) also utilities price was calculated under Colombian conditions. (Romero Pérez et al., 2017). For costs indexes was used Marshall and Swift (M&S) Equipment Cost Index in Chemical Engineering Magazine (www.chemengonline.com/pci-home). According to Eq. (1) the efficiency On-Stream was calculated. Eqs. (2) to (10) show economic indicators calculated, including the 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), return of investment (ROI) (Pérez-Zuñiga et al., 2016)

$$\eta_{On-stream}^{BEP} = \frac{m_{BEP}}{m_{max}} \tag{1}$$

$$DGP = \sum_i m_i C_i^v - TAC \tag{2}$$

$$PAT = DGP(1 - itr) \tag{3}$$

$$NVOC = \frac{AOC - FCH}{m_{RM}} \tag{4}$$

$$EP_1 = \sum_i m_i C_i^v - \sum_j m_j C_j^{RM} \tag{5}$$

$$EP_2 = \sum_i m_i C_i^v - \sum_j m_j C_j^{RM} - U \tag{6}$$

$$EP_3 = \sum_i m_i C_i^v - \mathrm{AOC} \tag{7}$$

$$CCF = \frac{\sum_i m_i C_i^v - \mathrm{AOC}}{TCI} \tag{8}$$

$$PBP = \frac{FCI}{PAT} \tag{9}$$

$$\%ROI = \frac{PAT}{TCI} * 100\ \% \tag{10}$$

Where $mBEP$ is the production capacity on BEP and m_{max} is the maximum production capacity, $m_i C_i^v$ is the product of product flowrate and its selling price, (Romero Pérez et al., 2017). TAC is the sum of operating and fixed total annualized costs of the process, itr is the tax rates, AOC are annualized operating costs, FCH are fixed charges, m_{RM} is the raw material flowrate, $m_j C_j^{RM}$ is the product of the flow of raw material and its selling price, U are the utilities costs, TCI is the total capital investment and FCI is the fixed capital investment (Pérez-Zuñiga et al., 2016).

3. Results

3.1. Economic evaluation

The assumptions for the chitosan production from shrimp shells wastes are shown in Table 1. The amount of 57,000 t was adjusted as a 10 % of shrimp production capacity in Colombia and adjacent countries as Ecuador, Brazil, Peru and Venezuela, and the chitosan production efficiency. In Table 2 is shown the TCI for chitosan production from shrimp shell wastes. Equipment is the highest costs compared to other factors that affect Direct Fixed Capital Investment (DFCI) due to the use of many heat exchangers, a few washing tanks, a crusher, six reactors and one dryer of 40 t/h. In addition, in Table 3 direct operating costs, fixed charges and general costs are shown. The cost of the raw material used includes the shrimp exoskeleton general cleaning, transportation of shrimp exoskeleton to the plant, necessary reagents for the depigmentation, demineralization, deproteinization, deacetylation and neutralization stages and the catalyzers for performing reactions required.

Table 1: Techno-economic assumptions for chitosan production from shrimp shell wastes plant

Processing capacity (t/y)	57,000
Main product flow (t/y)	12,152
Raw material cost (USD/t)	1,920
Final product cost (USD/t)	70
Plant life (y)	15
Salvage value	10 % of depreciable FCI
Construction time of the plant (y)	3
Location	Colombia
Tax rate	39 %
Discount rate	8.70 %
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)	20
Utilities	Steam, water, electricity, gas
Process fluids	Solid-liquid-gas
Depreciation method	Linear

Table 2: Total capital investment for chitosan production from shrimp shell wastes

Costs of capital investment	Total (USD $)
Delivered purchased equipment cost	97,228,628.20
Purchased equipment (installation)	19,445,725.64
Instrumentation (installed)	7,778,290.26
Piping (installed)	19,445,725.64
Electrical (installed)	12,639,721.67
Buildings (including services)	38,891,451.28
Services facilities (installed)	29,168,588.46
Total DFCI	224,598,131.14
Land	9,722,862.82
Yard improvements	38,891,451.28
Engineering and supervision	31,113,161.02
Equipment (R+D)	9,722,862.82
Construction expenses	33,057,733.59
Legal expenses	972,286.28
Contractors' fee	6,806,003.97
Contingency	29,168,588.46
Total IFCI	159,454,950.25
Fixed capital investment (FCI)	384,053,081.39
Working capital (WC)	230,431,848.83
Start up (SU)	38,405,308.14
Total Capital Investment (TCI)	652,890,238.36

Table 3: Annual total production at 100 % capacity

Operating Costs	Total (USD/y)
Raw materials	109,440,000.00
Utilities (U)	3,736,144.71
Maintenance and repairs (MR)	19,202,654.07
Operating supplies	2,880,398.11
Operating labor (OL)	397,800.00
Direct supervision and clerical labor	59,670.00
Laboratory charges	39,780.00
Patents and royalties	3,840,530.81
Direct production cost (DPC)	139,596,978
Depreciation (D)	26,203,115.30
Local taxes	11,521,592.44
Insurance	3,840,530.81
Interest/rent	6,528,902.38
Fixed charges (FCH)	48,094,140.94
Plant Overhead (POH)	238,680.00
Total Manufacturing Cost (TMC)	187,929,798.64
General Expenses (GE)	46,982,449.66
Total Product Cost (TPC)	234,912,248.30

3.2. Techno-economic sensitivity analysis

The techno-economic sensitivity analysis was based on the break-even point and the on-stream efficiency. Break-even analysis of production rate is shown in Figure 2, which is seen that the process is feasible operating under 100 % of installed capacity because production rate at the Break-even point is 18,700 t/y of shrimp shell wastes, also, the process is resist to the production capacity decrease, which is beneficial in case of decrease of availability shrimp shell wastes. Production capacity can decrease to a third-part of the total production capacity and not affect the operative costs, also, if the installed capacity is increase, will not affect the operating costs in the same proportion.

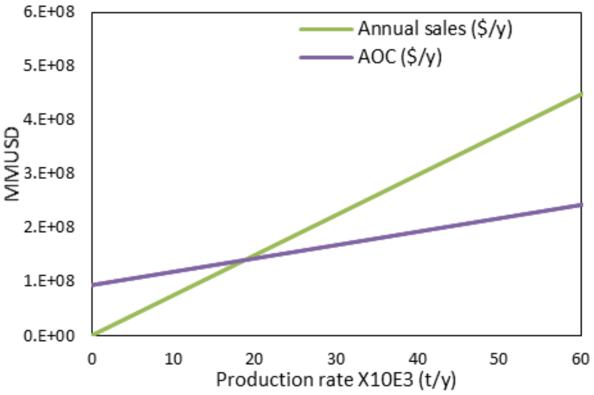
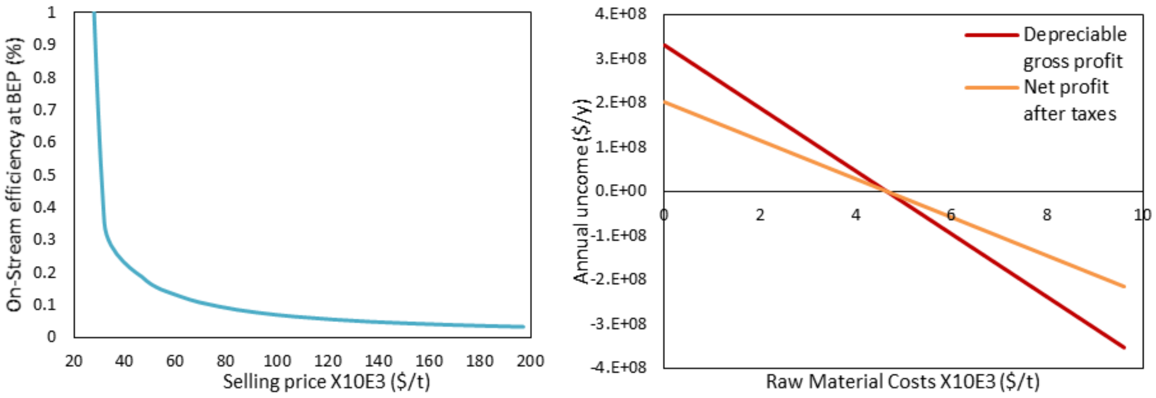


Figure 2: Break-even analysis of chitosan production from shrimp shell wastes

In figure 3a, how the chitosan price affects the On-stream efficiency percentage at Break-Even Point is shown. When selling price is between 20,000 and 50,000 USD/t, On-Stream Efficiency at Break Even Point is very sensible to the chitosan selling price, and an insignificant decrease of this price would do that, process reach the maximum production rate. The chitosan selling price stipulated was 35,000 USD/t, for that reason, the process has an On- Stream Efficiency of 15 % to reach the On-Stream Efficiency at Break Even Point which is 29.85 %. The selling price between 50,000 USD/t and 120,000 USD/t, is feasible because it is a confident zone and if the chitosan price decrease, the process will not be so affected. And finally, in the region of the selling price over 120,000 USD/t, the decrease of the chitosan selling price will not affect the On-Stream Efficiency at Break-Even Point.

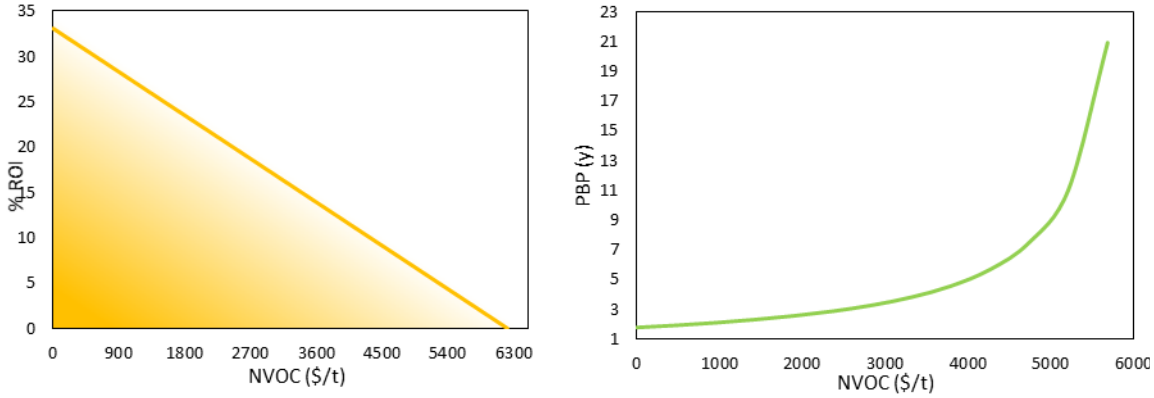
In Figure 3b, process sensitivity to changes in raw material costs is shown. The process has a high sensitivity to the raw material costs with a critical point in 50,000 USD/t, over that price, the process will have losses. The raw material cost stipulated was 1,920 USD/t, it is a competitive price because it can support a decrease of 50 % of itself and the process do not have losses.



(a) (b)

Figure 3: Effect of Chitosan Price and effect of raw material costs on On-Stream Efficiency percentage at Break Even Point and on process profitability. a) Effect of Chitosan Price on On-Stream Efficiency percentage at Break Even Point. b) Effect of raw material costs on process profitability

The influence of Operating costs on % ROI in Figure 4a is shown. The NVOC has a strong dependence with ROI, which can change the % ROI until 34 %. These NVOC have a critical point about 6,300 USD/t from which ROI get became null. In that process, the current NVOC is 3,277 USD/t, it is an excellent value because the current NVOC and the critical point both are far which do the process more confident, also, sensitivity analysis in payback period is shown in Figure 4b. When the operative costs are near to the chitosan selling price (in this process the operative costs are about 3,277 USD/t-raw material), the utilities get become to zero and FCI do not recovery which have effect in the PBP to trend to the infinity. Also, the process is stable until NVOC 3,000 USD/t, over that value it is a decontrol area.



(a) (b)

Figure 4. Sensitivity analysis for the effect of operating costs on the process ROI and the Payback Period. a) Effect of operating costs on the process. b) Sensitivity of PBP to operating costs ROI.

4. Conclusions

Chitosan production from shrimp shell wastes was performed using techno-economic sensitivity approach. For a flow rate of 57,000 t/y of exoskeleton under assumptions established the process is attractive, can be operated under maximum production capacity, it is stable to changes of the raw material costs. However, the cost of chitosan is a critical value, because a decrease in chitosan costs can affect the process profitability and the On-Stream Efficiency, so, it is recommended that the chitosan costs is between 50,000 USD/t and 120,000 USD/t and it is recommended that the operative costs have a lower value of 3,000 USD/t. If the operative costs increase, the process will not be feasible.

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