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Inherent safety Analysis and Sustainability Evaluation of Chitosan Production from Shrimp Exoskeleton in Colombia

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Abstract: The recovery and valorization of waste are some of the key aspects of sustainable production. The crustacean exoskeletons can be potentially used to obtain value-added products such as chitosan. A comprehensive analysis including both safety and sustainability aspects of chitosan production from shrimp shells is presented in this study. The inherent safety analysis and sustainability evaluation was performed using the Inherent Safety Index (ISI) methodology and the Sustainable Weighted Return on Investment Metric (SWROIM), respectively. The process was designed for a processing capacity of 57,000 t/y according to shrimp production in Colombia. The economic (%ROI), environmental (PEI output), energy (exergy efficiency), and safety (I_{TI}) technical parameters were included in the sustainability evaluation. The three first were obtained from the previous analysis performed by the authors. The total inherent safety index was estimated at 25 indicating that the process is inherently unsafe. The main process risks were given by the dangerous substance, reactivity, and inventory subindices. The overall sustainability evaluation showed a SWROIM of 36.23% indicating that the case study showed higher weighted performance compared to the return on investment (ROI) metric of 18.08%.

Keywords: inherent safety analysis; sustainability evaluation; SWROIM; shrimp exoskeleton; chitosan

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1. Introduction

Chitosan is a natural bioactive polymer that supports the structural components of the living organism, for example, crustaceans, insects, fungi, and some algae [1]. This biopolymer is considered one of the most important in the market, due to its inherent properties such as biocompatibility, biodegradability, absorption capacity, and antimicrobial activity [2]. Also, is known as a bioactive compound with biological anti-tumor, immune-enhancing, antifungal, antioxidant, and wound healing properties [3]. Therefore, natural sources such as chitin have been explored for chitosan production; on an industrial scale, the main source of chitin is the shells of the crustacean processing industries (shrimp, prawn, crab, and lobster) [4]. The main components of the crustacean exoskeletons are chitin, proteins, minerals, and carotenoids [5].

The shrimp farming and processing industry is the largest fishing industry in the world since shrimp represent approximately 45% of the total seafood consumed worldwide [6]. The current production of shrimp is estimated to be close to reaching 5.03 million tons per year [7] and demand is expected to continue growing in the coming years. In the case of Colombia, shrimp farming and processing are developed in areas around the Pacific Ocean, with an estimated rate of 2,400 t/year. However, huge amounts of wastes are generated during shrimp processing, representing about 65% of the initial weight of the shrimp including shrimp heads and shells [8]. The accumulation of these wastes generates environmental problems, also, their disagreeable odor stimulates the proliferation of insects, becoming a focus of diseases that can lead to a public health problem.

Chitosan from shrimp exoskeleton is obtained by a chitin deacetylation process [9] that includes the following stages: shells pretreatment, depigmentation, demineralization, deproteinization, and alkaline deacetylation [10]. The physicochemical characteristics of chitosan depend mainly on the deacetylation degree, the solution viscosity, the drying temperature, and the percentage of acid solution [11]. In this context, the design and implementation on an industrial scale of a chitosan production process from shrimp exoskeleton would improve the economics of crustacean processors and reduce to a minimum the potential for contamination of shrimp wastes [12]. Therefore, several works have been addressed to evaluate the economic, energetic, and environmental aspects of this process on a large scale. Meramo-Hurtado et al. [13] simulated a plant for chitosan production from shrimp exoskeleton in Colombia and carried out the environmental analysis and the exergy analysis, while Cogollo-Herrera et al. [14] performed the techno-economic evaluation of this same process.

In this work, it is proposed to perform the safety analysis and sustainability evaluation for the chitosan production process from shrimp exoskeleton. Furthermore, the available information will allow its development at industrial scale for chitosan production from shrimp exoskeleton. The Inherent Safety Index (ISI) Methodology proposed by Heikkilä, [15] is used to identify the intrinsic risks of the process and to propose improvements that allow the reduction of the hazards. The process sustainability is evaluated under economic, environmental, energy, and safety criteria. For a better interpretation of the sustainable performance of the process, the SWROIM presented by El-Halwagi is implemented [16]. The SWROIM has been used by other authors to evaluate and compare processes; Meramo-Hurtado et al. compared biobutanol production pathways via acetone-butanol-ethanol fermentation [17] and evaluated the sustainability of a lignocellulosic multi feedstock biorefinery [18].

This present study addresses a novel approach for the evaluation of a green-based production process, thus, the novelty of this research includes the scaling up of a sequence of steps previously performed at lab-scale, and the evaluation of this process from safety and sustainability viewpoints, for industrial-scale applications.

2. Materials and Methods

The methodology developed in this study aims to perform the safety analysis and the sustainability evaluation of chitosan production from shrimp exoskeleton in Colombia. The inherent safety analysis and the sustainability evaluation are carried out using the Inherent Safety Index (ISI) methodology and the Sustainable Weighted Return on Investment Metric (SWROIM), respectively. The criteria considered to evaluate the sustainability of the process are economic, environmental, energy, and safety. The information required to perform the safety analysis and the technical indicators (%ROI, PEI output, and exergy efficiency) for the sustainability evaluation were obtained from process simulation, techno-economic evaluation [14], environmental analysis, and exergy analysis [13] previously developed by the authors. The general methodology applied in this work is depicted in Figure 1.

 doi:10.20944/preprints202011.0612.v1

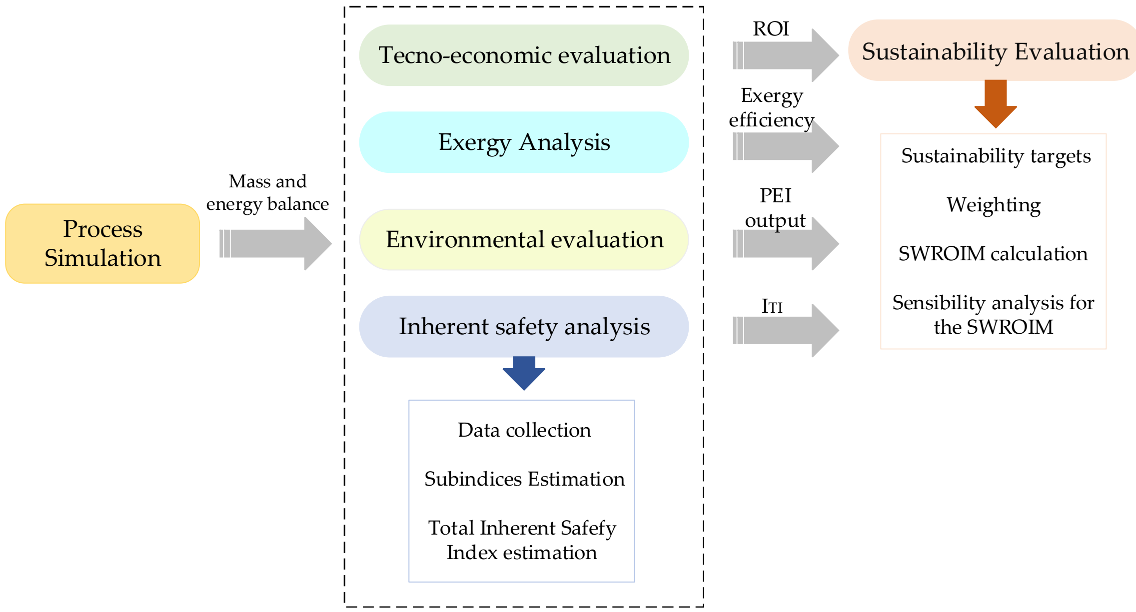

Figure 1. Schematic representation of the methodology

2.1. Process Description

The chitosan production process from shrimp exoskeleton was modeled based on information reported in literature and data obtained by the authors during the process synthesis under lab-scale conditions [19]. The processing capacity (57,000 t/y) was established assuming the availability of 10% of the shrimp production capacity in Colombia (and other countries near the Pacific). The chitosan production from shrimp shells includes five basic operations: pretreatment, depigmentation, demineralization, deproteinization, and deacetylation [10], as shown in Figure 2.

The shrimp exoskeleton is first subjected to physical pretreatment by washing, drying, and grinding to remove impurities and reduce its size to a powder of 0.5 mm [5]. In the depigmentation step, astaxanthin is removed from the treated exoskeleton using ethanol 85% vol [19]. Then, the shell powder is sent to the demineralization unit where removed calcium carbonate and other minerals using a 1.5 M hydrochloric acid solution to prevent chitin hydrolysis [20]. The mainstream goes to a deproteinization process where sodium hydroxide solution at 1M is added to remove the proteins and extract the chitin [21]. The extracted chitin is sent to the deacetylation step where the chitosan is obtained through the removal of acetyl groups [22]. The deacetylation reaction is carried out at 110°C, employing sodium hydroxide solution at 50%w/v with ratio chitin to solution of 1:10 w/v. After the reaction stages (demineralization, deproteinization, and deacetylation), the mainstreams are neutralized with HCl or NaOH and washed to adjust the pH to 7 [23]. Finally, the chitosan is dried in an oven at 100°C [24] and isolated for further commercialization.

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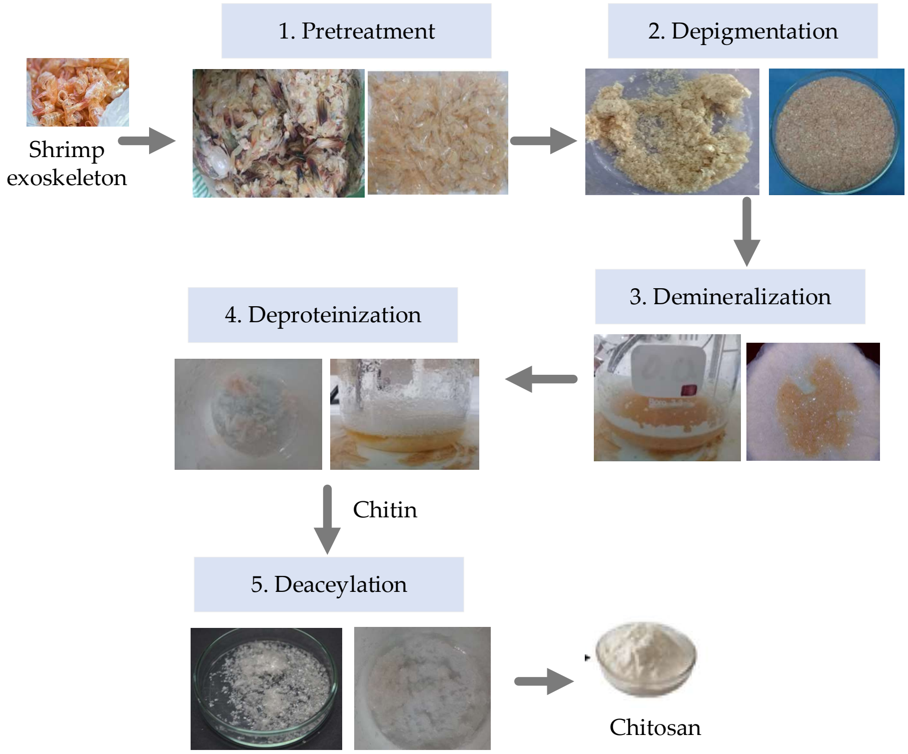

Figure 2. Process diagram for chitosan production from shrimp exoskeleton

2.2. Inherent Safety Analysis

Early hazard prevention during the chemical process design stage allows the development of processes inherently safer and more resistant to deviations or errors in operation without affecting the productivity or plant efficiency [25]. Hence, it is recommended that hazard elimination and risk reduction be carried out during the initial stage of process design [26]. The Inherent Safety Index (ISI) methodology allows evaluating processes in the conceptual design stage to identify intrinsic risks considering the worst-case scenario.

The Total Inherent Safety Index (I_{TI}) is defined as the sum of the Chemical Inherent Safety Index (I_{CI}) and the Process Inherent Safety Index (I_{PI}) by equation 1 [15].

$$I_{TI} = I_{CI} + I_{PI} \quad (1)$$

The chemical inherent safety index and the process inherent safety index are calculated as shown in equations 2 and 3, respectively. The first contains chemical factors such as reactivity, flammability, explosiveness, toxicity, and corrosiveness of chemical substances involved in the process; while the second contains subindices of inventory, process temperature, and pressure, equipment safety, and safe process structure. In table 1 are presented the symbols and scores for the safety subindices [15].

$$I_{CI} = I_{RM,max} + I_{RS,max} + I_{INT,max} + (I_{FL} + I_{EX} + I_{TOX})_{max} + I_{COR,max} \quad (2)$$

$$I_{PI} = I_{I} + I_{T,max} + I_{P,max} + I_{EQ,max} + I_{ST,max} \quad (3)$$

Table 1. Symbols and Scores for Inherent safety subindices.

Inherent safety subindices	Symbol	Score
Heat of main reaction	I_{RM}	0-4
Heat of side reaction	I_{RS}	0-4
Chemical interaction	I_{INT}	0-4
Flammability	I_{FL}	0-4

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Explosiveness	I_{EX}	0-4
Toxic exposure	I_{TOX}	0-6
Corrosiveness	I_{COR}	0-2
Inventory	I_I	0-5
Process temperature	I_T	0-4
Process pressure	I_P	0-4
Equipment safety	I_{EQ}	
Isbl		0-4
Osbl		0-3
Safe process structure	I_{ST}	0-5

2.3. Economic indicators

Techno-economic evaluation is used as a tool to determine the economic viability of engineering projects. Two types of primary costs are evaluated: Total Capital Investment (TCI) and Operating Costs (OC) [27]. The total capital investment refers to the money needed for the purchase and installation of the plant; while the operations costs refer to the money needed to maintain the plant in operation once the production starts [28]. Return on investment is an economic indicator to evaluate the profitability of the processes, which is calculated by equation 4 as follows.

$$\%\mathrm{ROI} = \frac{\text{Annual profit after taxes}}{\mathrm{TCI}} \mathrm{x}100 \quad (4)$$

2.4. Exergy Indicators

Exergy is defined as the maximum work that can be performed from the interaction between a thermodynamic system and a reference environment [29]. In chemical processes exergy is destroyed by irreversibilities; therefore, exergy analysis is a thermodynamic analysis method used to quantify the total process irreversibilities [30] and to evaluate novel technologies to provide key indicators to improve the design.

Exergy efficiency (η_{exergy}) indicates the process performance in terms of exergy flow, it is calculated by equation 5, where $\dot{Ex}_{total,in}$ is the total inlet exergy flow and $\dot{Ex}_{destroyed}$ is the total exergy destroyed (the difference between the total inlet and total outlet product exergy flow)

$$\eta_{exergy} = 1 - \left(\frac{\dot{Ex}_{destroyed}}{\dot{Ex}_{total,in}}\right) \quad (5)$$

2.5. Environmental Indicators

The environmental evaluation allows us to determine the environmental impacts of industrial activity and to provide solutions to adopt a sustainable development [31]. The Waste Reduction Algorithm WAR is a tool used to perform this kind of analysis, introduces the concept of Potential Environmental Impact (PEI) which can be calculated by product mass unit (kilograms) or time (hours) [32]. The PEI is considered from two points of view output and generated; the PEI output can be calculated by equations 6 and measures the environmental effects that the process emits and its use to improve the capacity of the process to obtain final products with a minimum discharge of potential environmental impact [33].

$$I_{out}^{(t)} = i_{out}^{(cp)} + I_{out}^{(ep)} + I_{we}^{(cp)} + I_{we}^{(ep)} = \sum_{j}^{Cp} M_j^{(out)} \sum_k X_{kj}\Psi_k + \sum_{j}^{ep-g} M_j^{(out)} \sum_k X_{kj}\Psi_k \quad (6)$$

Where $I_{out}^{(cp)}$ and $I_{out}^{(ep)}$ are the PEI output rates for the chemical process and the power generation process, respectively. $I_{we}^{(cp)}$ and $I_{we}^{(ep)}$ are the PEI associated with residual energy; M_j

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is the mass flow of the stream j; X_a is the mass fraction of a component an in the stream j; Ψ_k is the overall potential environmental impact of substance a k.

Also, The WAR uses eight impact categories to evaluate a chemical process: Human Toxicity Potential by Ingestion (HTPI), Human Toxicity Potential by Inhalation Dermal Exposure (HTPE), Aquatic Toxicity Potential (ATP), Terrestrial Toxicity Potential (TTP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Oxidation Potential (PCOP) and Acidification Potential (AP) [34].

2.5. Sustainability Evaluation

The Sustainable Weighted Return on Investment Metric (SWROIM) is used to determine a single value that shows the overall sustainable performance of the chitosan production process from shrimp exoskeleton. The approach proposed in this study involves economic, energy, environmental, and safety parameters. The SWROIM calculation follows the expression shown in equation 7 [35].

$$SWROIM = \frac{AEP\left[1 + \sum_{i=1}^{Nindicators} w_i \left(\frac{Indicator_i}{Indicator_i^{Target}}\right)\right]}{TCI} \quad (7)$$

Where AEP is the annual net profit of the project, w_i is the weighting factors of sustainability indicator i, $Indicator_i$ and $Indicator_i^{Target}$ are the current and target values of sustainability indicator i, respectively, and TCI is the total capital investment. The assignation of the values for w_i depends on the priority of the decision-makers [35]. The weighting factor works as follows: a value equal to 1 means that the parameter has the same relevance as the annual net profit of the project (AEP); while values below 1 mean to lower relevance.

3. Results and Discussion

3.1. Inherent safety analysis

The results are presented for the Chemical Inherent Safety Index (I_{CI}) and Process Inherent Safety index (I_{PI}). The worst scenario was assumed to calculate each indicator and to evaluate the maximum risk.

The chemical inherent safety index was measured by equation 2. The reactivity subindices are estimated by the exothermic grade of the main and side reactions. For this process, the main reactions occur in the demineralization, deproteinization, and deacetylation units; while the side reactions take place in the neutralization stages. The results reveal that the most exothermic main reaction was registered in the deacetylation step where the chitosan is obtained and that the side reactions are endothermic. Table 2 shows the chemical reactivity subindices assigned for this case study.

Table 2. Heats of reaction for chitosan production from shrimp exoskeleton

Main reaction	$C_8H_{15}NO_6 + NaOH \rightarrow C_6H_{13}NO_5 + C_2H_3NaO_2$	$\Delta H_\circ = -4{,}616.98\ J/g$ [a]
Side reaction	$HCl + NaOH \rightarrow NaCl + H_2O$	$\Delta H_\circ = 7{,}689.86 J/g$ [a]
$I_{RM,max}$	4	Extremely exothermic
$I_{RS,max}$	0	Endothermic

[a] value estimated by the author

The chemical interaction subindex ($I_{INT,max}$) refers to the chemical interactions from undesired reactions between substances and plant materials. In this case, the worst chemical interaction involves the formation of flammable gases; calcium chloride is present in the process, and in contact with water releases flammable vapor, therefore a score of 3 was assigned. The subindex of dangerous chemical substances is calculated for each component with information related to flammability, toxicity, and explosiveness characteristics. The flashpoint, TLV (8-hour Threshold Limit Value), and explosive limits were consulted in the safety data sheet of the components. Among all the substances present in the chitosan production from shrimp exoskeleton, the ethanol employed in the

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depigmentation step achieves the highest value in the general danger subindex, therefore, it is the most dangerous substance within the process. The rest of the substances showed to be safe due to their non-flammability, non-toxicity, and non-explosiveness nature. Table 3 shows the results obtained for the dangerous substance safety subindex.

Table 3. Safety parameters for dangerous substances

Substance	Ethanol[a]
Flash point (°C)	13.9
I_{FL}	3
TLV (ppm)	530.71
I_{TOX}	2
$(UEL - LEL)_{VOL\%}$	11.5
I_{EX}	1
$(I_{TOX} + I_{FL} + I_{EX})_{max}$	6

[a] Data taken from [36]

On the other hand, the corrosivity subindex evaluates the type of equipment construction material according to the handling needs of substances. This parameter is established considering the requirements for processing units. Table 4 presents a description of the equipment used for chitosan production. For this case due to the presence of corrosive substances such as chlorides and sodium hydroxide, in different stages, stainless steel was considered as the main construction material. Therefore, a score of 1 is assigned for this subindex. The inherent chemical inherent safety index was estimated at 14 as depicted in Figure 3.

Table 4. Description of the main equipment used for chitosan production from shrimp exoskeleton

Stage	Type of unit	Temperature (°C)	Pressure (kPa)	Material
Washing 1	Tank	25	101.32	Carbon steel
Drying 1	Dryer	107	101.32	Carbon steel
Crushing	Crusher	25	101.32	Carbon steel
Depigmentation	Mixer	25	101.32	Stainless steel
Demineralization	Reactor	25	101.32	Stainless steel
Neutralization 1	Reactor	25	101.32	Stainless steel
Washing 2	Tank	25	101.32	Stainless steel
Deproteinization	Reactor	90	101.32	Stainless steel
Neutralization 2	Reactor	25	101.32	Stainless steel
Washing 3	Tank	25	101.32	Stainless steel
Deacetylation	Reactor	110	101.32	Stainless steel
Neutralization 3	Reactor	25	101.32	Stainless steel
Washing 4	Tank	25	101.32	Stainless steel
Drying 2	Dryer	100	101.32	Stainless steel

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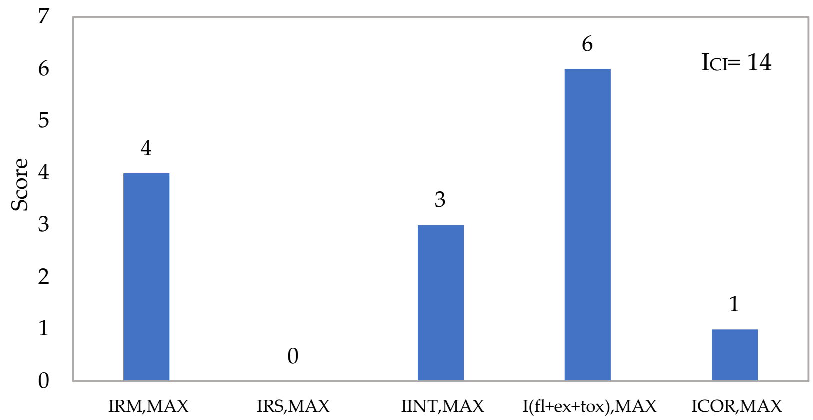

Figure 3. Subindices and total score for chemical inherent safety index

The process inherent safety index (I_{PI}) requires information associated with operating conditions, inventory, equipment type, and process structure. The temperature and pressure subindices were determined according to the maximum temperature and pressure registered in the process. The maximum temperature is reached in the deacetylation stage, the reactor operates at 110°C, thus a score of 1 was assigned. Also, the operational pressure was kept at atmospheric conditions (101.32 kPa), which represents no risk to the process. The inventory subindex measures the mass contained in any process equipment (tanks, reactors, mixers, and others) for a hydraulic retention time of 1 h [37]. A total inventory of 1,500 tones was calculated for the inside battery limits (ISBL); the outside battery limits (OSBL) were not considered in the inventory calculation due to the main processing units belongs to ISBL. Therefore, a score equal to 5 was assigned for the inventory subindex.

Another important parameter for calculating the inherent safety of the process is the equipment safety subindex (I_{EQ}). Based on the features of the equipment reported in table 4, I_{EQ} is assigned according to the most dangerous operational equipment. In this process, the reactors and dryers are the equipment with the highest potential risks, therefore, a value of 2 is assigned for this subindex. Finally, the safe structure subindex is determined by considering historical data and reports from heuristics and engineering experience of well-known processes [37]. However, there is no historical information related to the safety of a chitosan production process from shrimp exoskeleton, hence a neutral position is assumed. A score of 2 is assigned for this subindex which refers to novel or emerging large-scale processes. The process safety index was calculated at 11 as shown in figure 4.

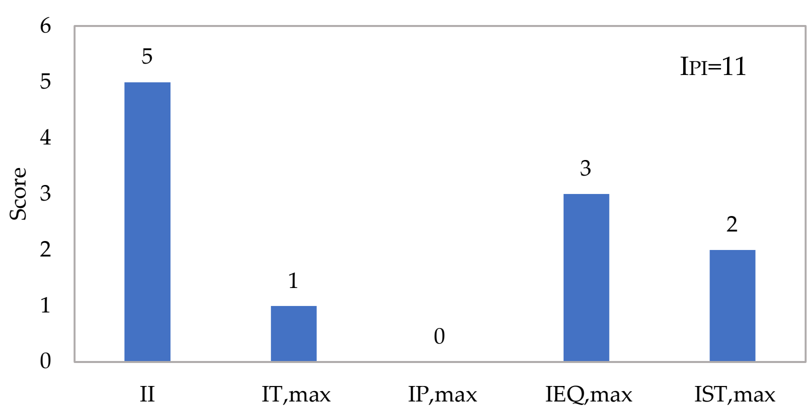

Figure 4. Subindices and total score for chemical inherent safety index

The total inherent safety index achieves for chitosan production from shrimp exoskeleton was 25, as presented in table 5. According to Heikkilä, [15] processes with I_{TI} higher than 24 are considered insecure; therefore, the results reveal that the process is inherently unsafe. The main process chemical risks were evidenced in the depigmentation step during ethanol storage, transport, and handling due to its high flammability and in the deacetylation unit given the extremely exothermic reaction that takes place. Furthermore, was found that in the process is handled large amounts of mass that represent a stressed factor for the safety of the plant; therefore, the most critical and risky operational variable is the inventory.

Table 5. Total inherent safety index

Index	Score
I_{CI}	14
I_{PI}	11
I_{TI}	25

Comparing the results with those obtained for the inherent safety analysis of a levulinic acid production process via acid-catalyzed ($I_{TI} = 24$) [37] and a bioethanol production process ($I_{TI} = 23$) [38], it is found that the process under study has a lower safety performance. Although substances of equal risk potential such as ethanol are involved and exothermic reactions are performed, these two processes handle lower inventories. For the chitosan production from shrimp exoskeleton, it is recommended to evaluate the use of less dangerous solvents in the depigmentation stage or to establish strategies for the safe handling of this substance, to constantly monitor the depigmentation and deacetylation step to minimize the risk associated with explosions or fires [39] and to reduce the processing capacity.

3.2. Sustainability evaluation

Sustainability for chitosan production from shrimp exoskeleton is evaluated through the return on investment percentage (%ROI), the total inherent safety index (I_{TI}), the exergy efficiency, and the total PEI output.

The techno-economic evaluation for the chitosan production process from shrimp exoskeleton was carried considering the United States dollar (USD) as the official currency, the useful life of the plant equal to 15 years, salvage value of 10%, construction time of 3 years, soft clay as the type of soil, 20 USD/h for the salary per operator, a discount rate of 8.7%, and a percentage of the contingency of 20%. The key results are shown in Figure 5.

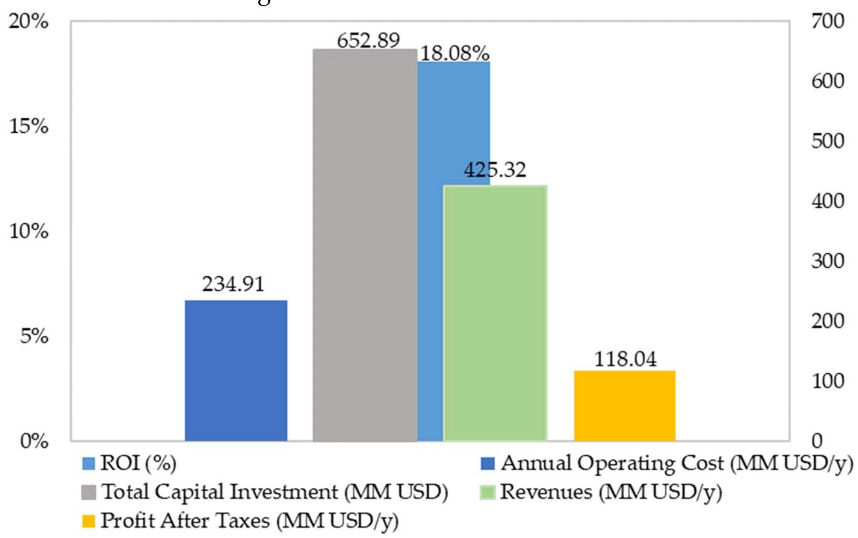

Figure 5. Summary of Economic Evaluation Results for the chitosan production from shrimp exoskeleton

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The return on investment percentage (%ROI) of 18.08% reveals that the process is economically attractive. Next, the potential environmental impact output and generated by the process were evaluated [13]; the key data and assumptions used in the environmental assessment include the use of oil as a fuel and the evaluation of energy and product stream contributions. The results are presented in figures 6 and 7.

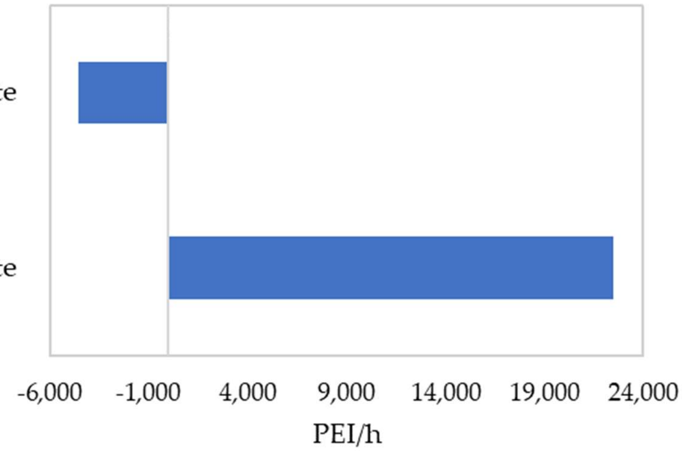

Figure 6. total generated and output rates of PEI for chitosan production from shrimp exoskeleton

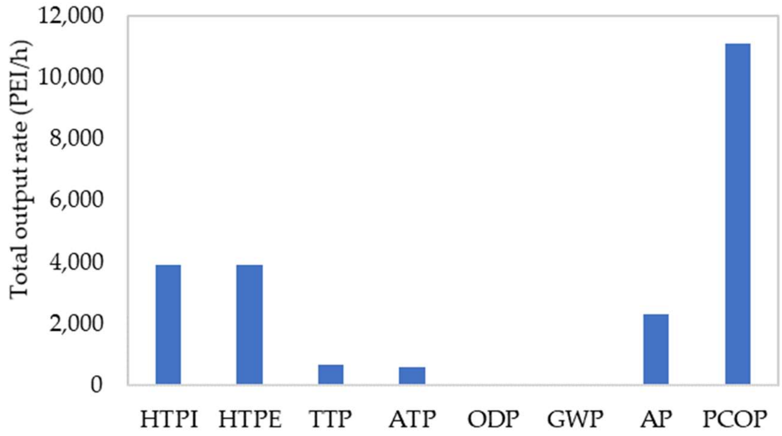

Figure 7. Categories environmental impacts for chitosan production from shrimp exoskeleton

The findings show that the process is friendly to the environment by obtaining negative rates of total PEI generation; while the potential environmental impact output was around 22,466.46 PEI/h. HTPI, TTP, and PCOP were the impact categories that contributed most to the rates of total PEI output due to the use of toxic chemicals such as ethanol, HCl, and NaOH in output streams. Next, the exergy analysis revealed that the process generates a large amount of irreversibilities due to the high exergy of wastes (1,008,733.92 MJ/h) which contributes to the process showing a low overall exergy efficiency (4.58%) as shown in figure 8. From the energy viewpoint, the process is not efficient; thus, it is mainly recommended to implement technical improvements in the most critical stages (depigmentation and deacetylation).

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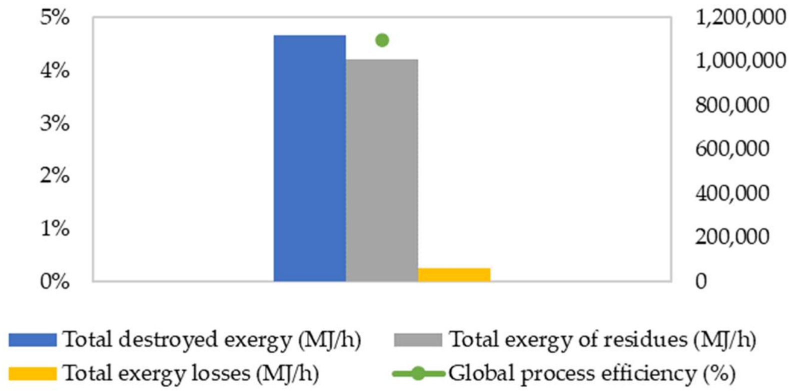

Figure 8. Global exergy results for chitosan production from shrimp exoskeleton

Next, The SWROIM is applied to evaluate the sustainability of the chitosan production process from shrimp exoskeletons. The target value for the inherent safety index (I_{TI}) was taken as 24 considering that a process is neutral in terms of inherent risks when it reports this score. For exergy efficiency, 100% was set as the target value; while a 50% reduction of the PEI output was established as the target for the environmental indicator. The weights w_{safety} , $w_{PEI\ Output}$ and w_{exergy} are taken as 1, assuming the importance of environmental conservation, reduction in energy consumption, and risk mitigation in the development of sustainable processes. Table 6 shows the indicators, target indicators, and weighting factors associated with each technical parameter.

Table 6. Corresponding parameters, indicators, and the weighting factor for each technical parameter

Parameter	index	$indicator^{i}$	$indicator^{target}$	W_i
Safety	Total inherent safety index (I_{TI})	25	24	1
Energy	Exergy efficiency (%)	4.58	100	1
Environmental	PEI output rate (PEI/h)	22,466.46	11,233.23	1

The results for the case study sustainability evaluation are depicted in figure 9. The findings reveal that the project achieved a sustainable performance of 36.23% which is higher than the value obtained for the return on investment (18.08%). This result might mean that the evaluated technical parameter had positive effects that yield the economic performance of the plant. Notably, there is a positive contribution associated with the reduction of total PEI output, an increase in exergy efficiency, and a reduction of inherent process risks. Also, compared to the SWROIM reported by a lignocellulosic multi feedstock biorefinery where economic, safety, energy, and environmental parameters were evaluated (27.29%) [18] indicate that chitosan production has a higher sustainable performance.

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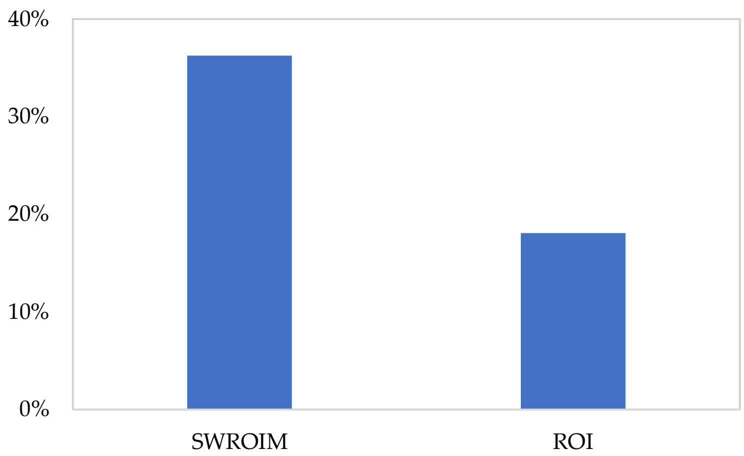

Figure 9. ROI and SWROIM for chitosan production from shrimp exoskeleton

Furthermore, to evaluate the effect of each technical parameter on the SWROIM, a sensibility analysis was performed by changing the value considered for the weighting factors. Three case studies were considered: the first case where the economic and energy aspects had the same relevance while the environmental and safety parameter value of 0.5. A second case where the environmental factor was of equal relevance to the economic parameter and a third case where the technical factor of safety had equal relevance to the economic factor. The results are presented in figure 10.

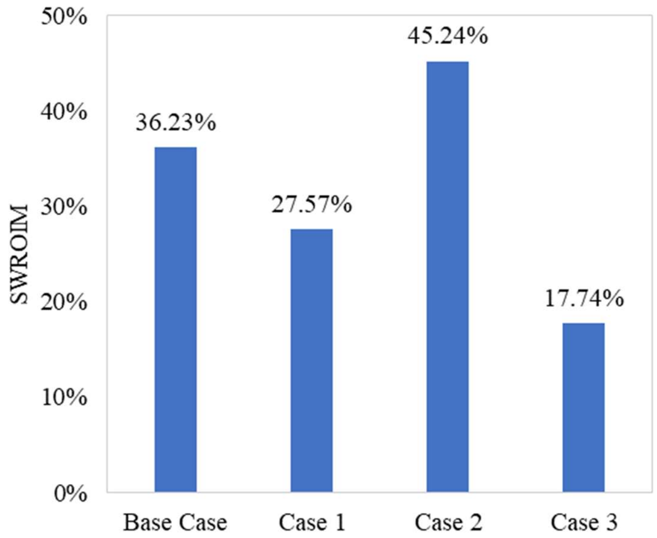

Figure 10. SWROIM sensibility analysis

The environmental parameter is the most decisive in the SWROIM result, considering the economic and environmental factor of equal relevance, the highest value is obtained (45.24%) given that the environmental conditions of the process are favorable. On the other hand, the safety indicator showed to be the weakest determinant on the SWROIM. For future studies, other essential parameters can be considered concerning process characteristics and model objectives to allow a broader sustainability analysis.

5. Conclusions

In this study, the inherent safety analysis and sustainability evaluation for the chitosan production process was performed using the inherent safety index methodology and the sustainable weighted return on investment metric, respectively. Economic, safety, energy, and environmental technical parameter were considered to evaluate the sustainability of the process. The economic, energy and environmental indicators were obtained from the previous works performed by the authors. The total inherent safety index was estimated at 25, which indicates that the process is inherently unsafe. The main chemical risks were identified in the depigmentation step due to the use of ethanol which is a highly dangerous substance and in the deacetylation reaction because it is extremely exothermic. Inventory was also found to be the riskiest operating variable within the process. The SWROIM showed a yield of 36.23% which reveals that the technical parameters evaluated have a positive effect on the return on investment of the process. The environmental parameter was the most determinant in this result given the good environmental performance described by the process. However, future studies need to be carried and other essential parameters can be considered concerning process characteristics and model objectives to allow a broader sustainability analysis. Also, the application of process intensification techniques might positively contribute to the ongoing development of this sector.

Author Contributions: Conceptualization, Á.D.G.-D., and K.A.M.-S.; methodology, K.A.M.-S., A.Z., and Á.D.G.-D.; software, Á.D.G.-D.; validation, K.A.M.-S., A.Z., and Á.D.G.-D.; formal analysis, K.A.M.-S., A.Z., and Á.D.G.-D.; investigation, K.A.M.-S., A.Z., and Á.D.G.-D.; resources, K.A.M.-S., A.Z., and Á.D.G.-D.; data curation, K.A.M.-S., A.Z., and Á.D.G.-D.; writing—original draft preparation, K.A.M.-S., A.Z., and Á.D.G.-D.; writing—review and editing, K.A.M.-S., A.Z., and Á.D.G.-D.; visualization, Á.D.G.-D., and A.Z.; supervision, Á.D.G.-D. and A.Z.; project administration, Á.D.G.-D.; funding acquisition, Á.D.G.-D. and A.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank the University of Cartagena and Sapienza University of Rome for providing equipment and software to successfully conclude this research.

Conflicts of Interest: The authors declare no conflict of interest.

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