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Inherent safety analysis and sustainability evaluation of dual crude palm and kernel oil production in North Colombia

Análisis de seguridad inherente y evaluación de sostenibilidad de la producción dual de aceite crudo de palma y palmiste en el Norte de Colombia

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Abstract

Currently, Colombia is the fourth country in African palm production worldwide. The generation of value-added products from residual biomass is one of the specific demands; therefore, this work aims to perform the inherent safety analysis and the sustainability assessment of dual crude palm and kernel oil production. The kernel oil is extracted from the palm cake processing. 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 sustainability of the process was evaluated through economic, environmental, energetic, and safety indicators. The total inherent safety index achieved was 12 indicating an inherently safe performance for the process. The main process risks were given by the safety equipment and inventory subindices; the chemicals involved in the process represented no risk. The overall sustainability evaluation showed a SWROIM of 76.01% which reveals a positive contribution of the indicators considered on the return on investment; hence, it was found that the process is sustainable. The novelty of this work lies in providing knowledge to satisfy the demands of the palm chain to contribute to the improvement of the agricultural sector in Colombia.

Keywords: inherent safety analysis, sustainability, SWROIM, palm oil, kernel oil, African palm, productive chains.

Resumen

Actualmente, Colombia es el cuarto país en producción de palma africana a nivel mundial. La generación de productos de valor agregado a partir de la biomasa residual es una de las demandas específicas; por lo tanto, este trabajo tiene como objetivo realizar el análisis de seguridad inherente y la evaluación de la sostenibilidad de la producción dual de aceite crudo de palma y aceite de almendra. El aceite de semilla se extrae del procesamiento de la torta de palma. El análisis de seguridad inherente y la evaluación de sostenibilidad se realizaron utilizando la metodología del Índice de seguridad inherente (ISI) y la Métrica de retorno ponderado sostenible de la inversión (SWROIM), respectivamente. Se evaluó la sustentabilidad del proceso a través de indicadores económicos, ambientales, energéticos y de seguridad. El índice de seguridad inherente total alcanzado fue de 12, lo que indica un rendimiento inherentemente seguro para el proceso. Los principales riesgos de proceso estuvieron dados por los subíndices de equipos de seguridad e inventarios; los químicos involucrados en el proceso no representaban ningún riesgo. La evaluación global de sostenibilidad mostró un SWROIM de 76,01% lo que revela una contribución positiva de los indicadores considerados sobre el retorno de la inversión; por lo tanto, se encontró que el proceso es sostenible. La novedad de este trabajo radica en brindar conocimiento para satisfacer las demandas de la cadena de la palma para contribuir al mejoramiento del sector agropecuario en Colombia.

Palabras clave: análisis de seguridad inherente, sustentabilidad, SWROIM, aceite de palma, aceite de almendra, palma africana, cadenas productivas.

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1 Introduction

In recent years, rural development policies in Latin America have been constantly evolving to provide conditions favorable for the development of more competitive global economies. The performance of initiatives to promote the creation of production chains in the agricultural sector around strategic products has been one of the main emphasis areas of these politics (Mahlknecht *et al.*, 2020). In Colombia, the enhancement of the agricultural sector is a politic embodied in the National Development Plan 2014-2018; however, it was found that productive chains in the country have certain unsatisfied demands, which affect their competitiveness in the global market.

Colombia leads African palm production in Latin America and is the fourth-largest producer worldwide after Indonesia, Malaysia, and Thailand with 2% of global production (Potter *et al.*, 2020). African palm is the second most important crop in Colombia after coffee (Dishington, 2020). These plantations are found in four main regions of the country: north, center, east, and southwest (Ocampo-Peñuela *et al.*, 2018). Nevertheless, the largest oil palm crop is located within nine departments of the North region (Castiblanco *et al.*, 2015). African palm plantations in Colombia are destined for palm oil production (González-Delgado *et al.*, 2021), from which rachis, palm cake, sludge, and wastewater are obtained as waste (Nahrul *et al.*, 2020). Palm oil is the largest commercialized vegetable oil in the world, representing about 29.60% of the global oil and fat production (Rivera-Méndez *et al.*, 2017). It constitutes a valuable product widely used as part of a huge amount of products used daily in the biofuel, food, and body care sectors (Esan *et al.*, 2022; Landazury *et al.*, 2022). Palm oil is considered an economic driver and its production represents an important activity for the social and economic growth of Colombia (Landazury *et al.*, 2022). Therefore, alternatives to supply the unsatisfied demands in the palm chain should be analyzed.

Reducing dependence on fertilizers, the sustainability of agro-industrial activity, technological innovation in palm cultivation and processing, efficiency in energy use, implementation of production plans to obtain value-added products from the residual biomass, and implementation of strategies to reduce costs are the specific demands of the palm chain (Miniagricultura,2020). Considering the above, through the application of synthesis, analysis, and evaluation methodologies, it is aimed to generate solutions to some of these demands (obtaining value-added products from the residual biomass). This work aims to evaluate the inherent safety and the sustainability of the dual crude palm and kernel oil production process using the Inherent safety Index (ISI) methodology and the Sustainable Weighted Return on Investment Metric (SWROIM), respectively, to identify the risks and the sustainability of the process when processing waste such as palm cake and find improvement opportunities to allow the continued expansion of the palm sector.

As an extension of social aspects, safety evaluation allows the identification of hazards with the potential to affect the sustainability of the process (Moreno-Sader *et al.*, 2020); while sustainability assessment allows a complete analysis relating economic, energy, environmental, and safety aspects. Different methodologies and indices have been developed to evaluate the safety performance of chemical processes including the Dow Fire and Explosion Index (Dow F& EI), the Numerical Descriptive Inherent Safety Technique (NuDIST), Safety Weighted Hazard Index (SWHI) (Yuan *et al.*, 2022), the Inherent Safety Index (ISI) (Pu *et al.*, 2023), among others. Zuorro *et al.* (2020) used the inherent descriptive numerical safety technique to evaluate the safety of chitosan production from shrimp exoskeletons. The results revealed that the highest risk of explosion and fire is located at the depigmentation and demineralization stages. Moreno-Sader *et al.* (2020) applied the Hazard Identification and Ranking (HIRA) methodology to identify critical stages and propose safety corrections for a crude palm oil production process in Colombia. The findings showed fire and explosion risks in the process due to combustible dust emissions and flammable material handling. Ahmad *et al.* (2016) evaluated the inherent safety of several biodiesel production pathways from the flammability parameter perspective using the (NuDIST) technique; the results showed that the most dangerous via corresponds to acid-catalyzed transesterification using fresh vegetable oil (PP4). Also, there are different methodologies in the literature to assess the sustainability of chemical processes. Syihabuddin *et al.* (2020) analyzed the sustainability of two methanol production routes using the Sustainability Evaluator (SE) which included economic, environmental, and social impacts; the natural gas path was found to be more sustainable. While Meramo *et al.* (2020) used SWROIM to compare two butanol production alternatives from a sustainability viewpoint. The evaluation involved economic, environmental, energy, and safety aspects.

This is the first time that the inherent risks of dual crude palm and kernel oil production process are evaluated using the inherent safety index methodology. Besides, the sustainability evaluation will allow to include different criteria that allow a complete diagnosis of the process. The novelty of this work lies in providing knowledge to satisfy the demands of the palm chain to contribute to the improvement of the agricultural sector in Colombia.

Considering the above, in the broader context of the palm oil industry in Colombia, sustainability and responsible development are paramount. While efforts have been made to address environmental and social concerns, significant challenges persist. To advance the sector, future research and initiatives should prioritize sustainable land use practices, biodiversity conservation, and responsible social and labor practices. Exploring innovative technologies for resource efficiency, waste reduction, and environmental impact mitigation is essential. Collaboration among industry stakeholders, government, and communities is crucial for implementing best practices and transparent supply chains. Diversifying palm oil-derived products and exploring alternative applications can enhance industry resilience.

Additionally, given the global shift away from palm oil in biofuels, identifying alternative markets is strategically wise for long-term viability. Specially, if it is considered that the European Commission?s Delegated Regulation from March 13, 2019, recognizes palm oil as a high-risk raw material of indirect land use change (ILUC) (Commission Delegated Regulation, 2019). This perspective reflects the concern that palm oil production can indirectly lead to deforestation and land use changes elsewhere, which can have profound environmental consequences and contribute to increased carbon emissions. This has led to a planned gradual reduction in the use of palm oil-derived biofuels at the European level. Addressing these sustainability issues requires a multi-faceted approach. Environmentally, there is a need for stricter regulations and enforcement to prevent deforestation and protect biodiversity. Socially, the rights and livelihoods of local communities and workers must be respected. Economically, the industry must ensure fair trade practices and explore alternative revenue streams, such as the use of by-products. Additionally, greater transparency and traceability in the supply chain can help ensure responsible sourcing and production practices. These measures can contribute to making the palm oil industry more sustainable.

Colombia's palm oil industry holds great growth potential but must prioritize sustainability and the well-being of all stakeholders. Future research should target efficient, eco-friendly extraction methods and innovative by-product utilization. Assessing social impacts, labor conditions, and community relations is imperative. Stronger regulations and enforcement are needed to curb deforestation and protect biodiversity. Transparency and traceability within the supply chain are crucial for responsible sourcing and production. These measures can position the Colombian palm oil industry as a global leader in sustainable and ethical production and can help the Colombian palm oil industry strike a balance between economic growth and environmental and social responsibility.

2 Materials and methods

The methodology developed in this study includes:

1. Inherent safety analysis of dual crude palm and kernel oil production process.

2. Sustainability assessment of dual crude palm and kernel oil production process.

2.1 Process description

The dual crude palm and kernel oil production process was modeled based on data from the operating conditions and processing stages of several plants in Northern Colombia and information reported in the literature. The process diagram is presented in Figure 1, with the main mass flows of the streams. The extended mass balance is presented in the supplementary materials, including conditions of pressure, temperature and the mass fraction of the components considered during the simulation.

To produce crude palm oil, the African palm bunch (30t/h) is sterilized in the first stage with saturated steam to hydrolyze the palm rachis, soften the tissues of the pulp, and avoid the effect of the enzyme lipase on the fatty acids (Alvarez-Cordero *et al.*, 2017). Next, the sterilized bunches are sent to the second step (threshing) where the fruits are separated from the palm rachis. The separated fruits are reheated in the third unit (digestion) and sent to a pressing process where a liquor rich in palm oil is extracted, and palm cake is obtained; the last one is processed for the extraction of kernel oil. The press liquor goes to the clarification stage, where water is added to dilute it and allow the oil separation and purification. During clarification, about 90% of the oil is separated and pumped to the drying step. The heavy sludge from the clarification unit goes to the next stage (centrifugation), where 10% of the oil is recovered and recirculated to the clarification step; the water and heavy sludge leave the process. In the drying unit, the moisture in the oil is removed; due to the high oil temperature, drying is carried out under vacuum conditions, which causes the remaining water to evaporate. Finally, the extracted crude palm oil (2.28 t/h) is stored.

To produce palm kernel oil, the palm cake is initially subjected to a separation process to separate the fiber from the nut. The separated fiber is burned in a boiler, while the nut is sent to a subsequent stage (almond separation) where steam enters, and the almond is separated from the shell.

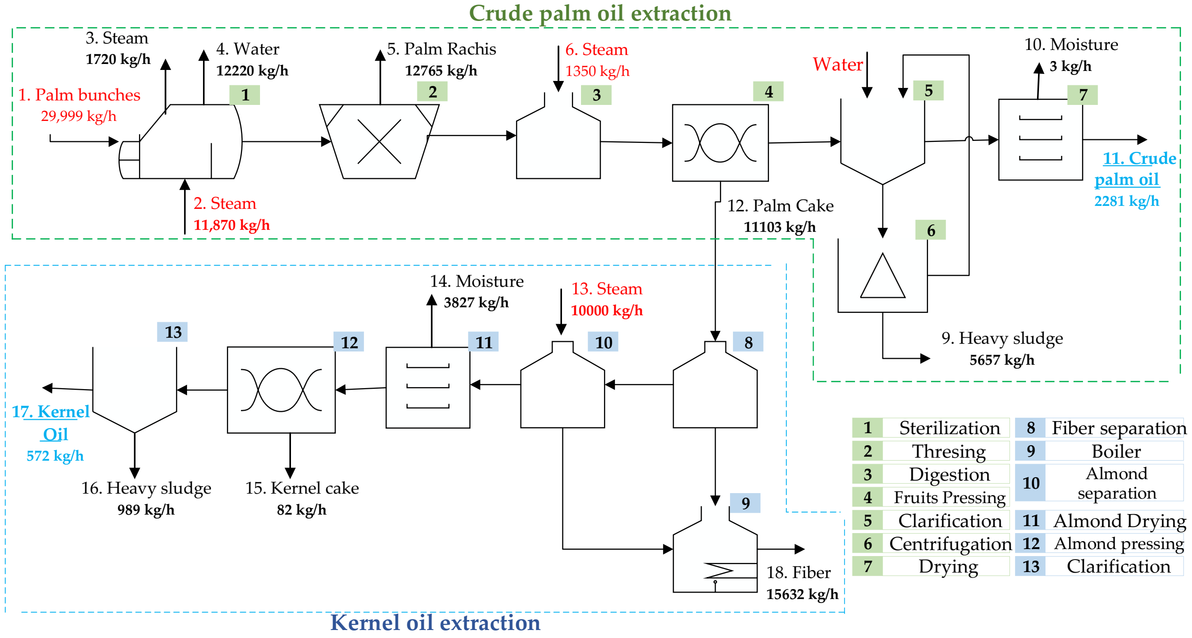

Figure 1. Process diagram for dual crude palm and kernel oil production.

The shell is burned in the boiler, while the almond is sent to a dryer to remove excess moisture. Then, the dry almonds are pressed to extract the oil content from them. The kernel cake is discarded, and the liquor rich in kernel oil is subjected to a clarification process to purify the kernel oil. Finally, the kernel oil is obtained (0.57 t/h) and stored.

2.2 *Inherent safety analysis*

The inherent safety of a chemical process is related to its intrinsic properties (use of chemicals and safer operations). The objective of inherent safety is to avoid and eliminate risks by reducing hazardous material and operations in the plant instead of controlling them through additional protection systems (Ahmad *et al.*, 2020). For the safety analysis of the dual crude palm and kernel oil production process, the Inherent Safety Index (ISI) methodology is used (Pu *et al.*, 2023).

The ISI methodology includes the total inherent safety index calculation_(I_{TI}), which indicates whether a process is inherently safe or inherently unsafe ($I_{TI} \leq 24$ the process is inherently safe, and $I_{TI} > 24$ the process is inherently unsafe). The I_{TI} encompasses the calculatingon of the chemical safety index (I_{CI}) and the process safety index (I_{PI}). The first is determined from the contribution of parameters such as heat of reaction, flammability, toxicity, explosiveness, and chemical interaction of the chemicals involved in the process. The second is evaluated based on process parameters such as inventory, maximum temperature and pressure, equipment safety, and process structure.

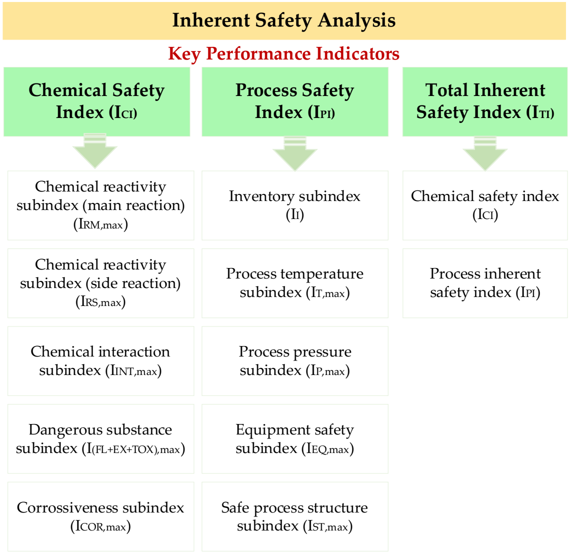

Figure 2. Key performance indicators of ISI methodology.

Figure 2 presents the subindices required for the key critical performance indicators calculation.

The total inherent safety index is calculated by assessing the worst possible scenario that may arise. Therefore, the highest sum of flammability, explosiveness, and toxicity is used in the calculations. For the temperature and pressure subindices, the maximum recorded process pressure and temperature are utilized, respectively. The inventory subindex measures the mass contained in the equipment during a 1-hour retention time (Meramo-Hurtado *et al.*,2019). Also, the most dangerous chemical interaction between chemicals and plant materials, the most unsafe equipment, and the worst process structure are considered. The scoring for each subindex is performed according to specific weights (Pu *et al.*,2023).

2.3 *Sustainability assessment*

The sustainability assessment of the dual crude palm and kernel oil production process uses the Sustainable Weighted Return on Investment Metric (SWROIM) (Guillen-Cuevas *et al.*, 2018). The SWROIM allows for determining a single value that shows the sustainable performance of a process. Equation 1 presents the expression to calculate the SWROIM.

$$SWROIM = ROI\left[1 + \sum_{i=1}^{Nindicators} w_i\left(\frac{Indicato_i}{Indicator_i^{Target}}\right)\right] \tag{1}$$

Where ROI is an economic indicator that indicates the profitability of a 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. ROI is calculated as the ratio of annual profits after taxes (PAT) to total capital investment (TCI), as shown in equation Equation 2.

$$ROI = \frac{PAT}{TCI} \times 100\% \tag{2}$$

The general methodology to determine the SWROIM is presented in Figure 3.

The value of w_i is assigned according to the priorities of the decision-makers in the project. Values equal to 1 mean the indicator has the same relevance as the economic factor within the project.

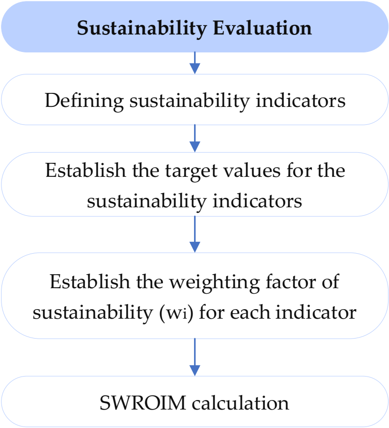

Figure 3. Methodology for SWROIM calculation.

In contrast, values below 1 for an indicator mean lower relevance compared to the economic parameter. The sustainability indicators considered to evaluate the sustainability of the process include exergy efficiency, the potential environmental impacts output (PEI output), and the total inherent safety index. The sustainability indicators are defined as follows.

Exergy efficiency is a measure of process performance from the energy viewpoint. Exergy is the maximum work that can be achieved from the interaction of a thermodynamic system and its reference environment (Ağbulut, 2022). When the state of a quantity of matter is different from the reference environment, the possibility of producing work exists. In chemical processes, there is the destruction of exergy due to irreversibilities; through an exergy analysis is possible to determine the process exergy efficiency and identify and quantify the primary sources of irreversibilities. Exergy efficiency is defined by Equation 3 as the ratio between the exergy destroyed ($\dot{E}x_{destroyed}$) and the total inlet exergy flow ($\dot{E}x_{total,in}$) (Meramo-Hurtado *et al.*, 2020a).

$$\eta_{exergy} = 1 - \left(\frac{\dot{E}x_{destroyed}}{\dot{E}x_{total,in}}\right) \tag{3}$$

The PEI output allows for determining the external environmental efficiency of the process, in other words, the capacity to obtain final products at a minimum potential environmental impact of discharge (Herrera-Aristizábal *et al.*, 2017). The concept of potential environmental impact (PEI) is introduced by the waste reduction algorithm WAR (a tool to analyze the environmental impacts of processes). PEI output follows the expression given in Equation 4.

$$I_{out}^{(t)} = \sum_{j}^{Cp} M_j^{(out)} + \sum_k X_{kj}\psi_k + \sum_{j}^{ep-g} M_j^{(out)} \sum_k X_{kj}\psi_k \tag{4}$$

M_j is the mass flow of the stream j; X_{kj} is the mass fraction of component k in the stream j; Ψ_k is the overall potential environmental impact of substance k. Besides, the potential of environmental impact is evaluated through 8 impact categories: 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).

Table 1. Calculated subindices for chemical inherent safety and process inherent safety indexes.

Chemical Safety Index (ICI)	Score	Process Inherent Safety Index (IPI)	Score
Chemical reactivity (main reaction)	0	Inventory	3
Chemical reactivity (side reaction)	0	Process Temperature	2
Chemical interaction	1	Process pressure	0
Dangerous substance	1	Equipment safety	4
Corrosiveness	0	Safe process structure	1
Total	2	Total	10

Table 2. Description of equipment for dual crude palm and kernel oil production.

Stage	Type of unit	T (°C)	Pressure (kPa)	Inventory (t)	Material
Sterilization	Tank	133.18	101.32	38.18	Carbon steel
Threshing	Mill	133.18	101.32	27.93	Carbon steel
Digestion	Tank	95	101.32	16.51	Carbon steel
Fruits pressing	Press	105	101.32	16.51	Carbon steel
Clarification	Decanter	91.85	101.32	8.57	Carbon steel
Centrifugation	Centrifuge	91.85	101.32	6.29	Carbon steel
Drying	Dryer	91.85	97.8	2.28	Carbon steel
Fiber Separation	Separator	95.85	101.32	11.10	Carbon steel
Boiler	Boiler	157	101.32	15.63	Carbon steel
Almond Separation	Separator	95	101.32	19.27	Carbon steel
Almond drying	Dryer	101	101.32	5.47	Carbon steel
Clarification	Decanter	101	101.32	1.56	Carbon steel

3 Results and discussion

3.1 *Inherent safety analysis*

The results for the chemical safety index and the process safety index of the dual crude palm and kernel oil production are presented in Table 1. During the extraction of crude palm and kernel oil, no chemical reaction take place. Therefore, the subindices of chemical reactivity are all zero. The chemical interaction subindex reached a score of 1, given that, based on the analysis of possible undesired reactions, the most dangerous interaction was represented by the formation of non-flammable vapors. The dangerous substance subindex was estimated by analyzing the flashpoint, the upper (UEL) and lower (LEL) explosion limits, and the toxicity according to the TLV (8-hour toxic exposure limit) for each chemical. The analysis showed that chemicals involved in producing crude palm and kernel oil have non-flammable, non-toxic, and non-explosive characteristics. Palmitic acid, stearic acid, oleic acid, linoleic acid, and myristic acid, contained in the crude palm and kernel oil, are combustible substances (flash point > 55°C) according to which a score of 1 is assigned for the dangerous substance subindex.

The corrosiveness subindex is calculated according to the type of construction material of the plant equipment. Table 2 describes the equipment used in the dual crude palm and kernel oil production. Considering the non-corrosive nature of the chemicals and the operating conditions, carbon steel is selected as the construction material of the equipment, and a score of 1 is assigned for this subindex.

The total process inventory was calculated at 170.94 t; therefore, a score of 3 was assigned for the inventory subindex. The maximum temperature of the process was recorded in the boiler where the fiber and shell are burned (157°C); thus, a value of 2 is assigned for this subindex. The pressure in the process is maintained at 101.32 kPa in most stages and 97.8 kPa in the crude palm oil drying unit; accordingly, a value of 0 is assigned for the pressure subindex. The safety equipment subindex calculation involves evaluating the different equipment; it was found that the most unsafe equipment in the dual crude palm and kernel oil production process are the dryers and the boiler; hence, a score of 4 is assigned. Finally, the process safe structure subindex is set equal to 1, considering that the process is a common practice in engineering and there is no information about accidents.

The dual crude palm and kernel oil production process showed a total inherent safety index of 12 with a contribution of 2 for the chemical safety index and 10 for the process safety index, as presented in Figure 4. According to the results, it was determined that the process is inherently safe. The chemicals involved in the process were shown to be relatively safe and do not represent risks given their characteristics.

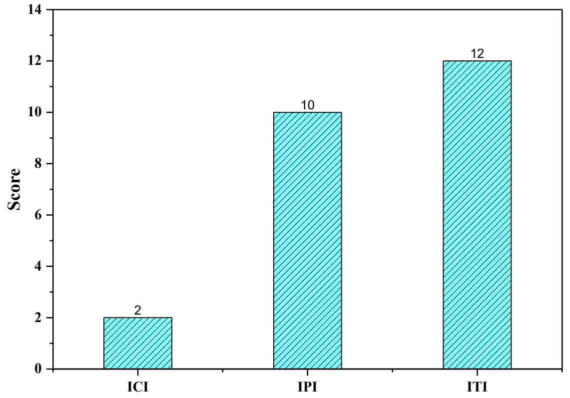

Figure 4. Total inherent safety index for dual crude palm and kernel oil production.

However, the most critical conditions were represented by the equipment used to dry the crude palm oil and almonds and the boiler where the fiber and the shell were burned. Besides, these stages register the most critical operating conditions. The inventory also represents a critical variable in the process. The amount of material handled in the system is considerably high, compromising the overall plant safety as it represents a stress factor for all the equipment. Applying the ISI method to the natural separation process of 2-phenyl ethanol using ethanol revealed that the process streams flagged as hazardous encompass the extract and solvent recycling streams (Chacón-Izquierdo *et al.*, 2022).

The dual crude palm and kernel oil production process was shown to be inherently safer compared to similar processes such as bioethanol production from palm rachis (I_{TI} = 23) (Sanjuan *et al.*, 2018), levulinic acid production from the banana rachis (I_{TI} = 24) (Meramo-Hurtado *et al.*, 2019), and a biorefinery for ethanol, levulinic acid, butanol, succinic acid, and hydrogen production from lignocellulosic biomass (I_{TI} = 36) (Meramo-Hurtado *et al.*, 2020b), where the most unsafe conditions are given by chemical reactivity and dangerous substances subindices. It is mainly highly recommended for the process to closely monitor the drying operations and the boiler to avoid prevent incidents and to decrease theoptimize processing capacity. In addition, the results obtained in the present study were lower than the reported for the production of producing whey syrups and protein concentrate considering the stand-alone process and process attached to a cheese production plant (Gómez *et al.*, 2020).

The sustainability assessment of the biofuel production process involved the utilization of environmental and safety indicators to quantify social consideration, employing the WAR and ISI methods. Two technologies for biodiesel production were evaluated: transesterification and heterogeneous catalysis, which yielded PEI output rates of 146.7 PEI/h and 137.7 PEI/h, respectively. The safety analysis did not show significant differences due to the presence of methanol in both processes, resulting in an ISI of 17. Both results surpass those obtained in the current study, demonstrating a favorable performance of the dual process for obtaining crude palm and kernel oil (Li *et al.*, 2011).

3.2 Sustainability evaluation

The corresponding values of the sustainability indicators ($Indicator_i$) are presented following; these show the current performance of the dual crude palm and kernel oil production process. The ROI of the dual crude palm and kernel oil production is calculated by Equation 2 as follows.

$$ROI = \frac{27{,}543{,}279.63}{11{,}336{,}405.46} \times 100\% \tag{5}$$

$$ROI = 41.16\% \tag{6}$$

The exergy efficiency is calculated according to Equation 3 as follows. The exergy destroyed in each process stages are presented in Table 3.

$$\eta_{exergy} = 1 - \left(\frac{495{,}646.44}{606{,}921.09}\right) \tag{7}$$

$$\eta_{exergy} = 18 \tag{8}$$

Table 4 presents the PEI output by impact category; the total PEI output from the process was calculated at 2.60×10^{-4} PEI/h. $Indicator_i^{Target}$. Some assumptions were established to evaluate the overall sustainability of the process; it is essential to mention that the production plants implemented in Colombia are in rural areas in the northern region where the availability of raw materials is broad. Therefore, the weighting factor for the safety indicator is considered of maximum relevance. For the environmental indicator,

Table 3. Exergy destroyed by stages in dual crude palm and kernel oil production.

Stage	Exergy destroyed (MJ/h)
Sterilization	16,894.66
Threshing	258,300.84
Digestion	3,962.41
Fruits pressing	907.41
Clarification	2,469.37
Centrifugation	2,197.13
Drying	65.85
Fiber Separation	158.15
Boiler	195,856.21
Almond Separation	12,635.40
Almond drying	452.22
Almond pressing	1,138.38
Clarification	608.41
Total	495,646.44

Table 4. PEI output by impact category of dual crude palm and kernel oil production.

Impact category	PEI output (PEI/h)
HTPI	3.91×10^{-5}
HTPE	2.25×10^{-5}
ATP	2.95×10^{-5}
TTP	3.91×10^{-5}
GWP	2.38×10^{-8}
ODP	0.00
AP	1.30×10^{-4}
PCOP	0.00
Total	2.60×10^{-4}

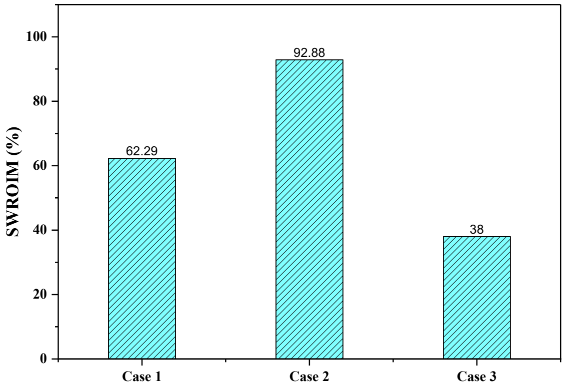

Figure 5. SWROIM sensibility analysis.

the weighting factor is established of maximum relevance considering the commitments acquired by Colombia in different international agreements about environmental protection. Moreover, considering the importance of the energy factor in the development of sustainable processes, the weighting factor for this indicator is also considered of maximum relevance.

Table 5 presents the indicators, target values for the indicators, and the weighting factors assigned. The findings reveal that the process achieves a sustainable performance of 76.01%, higher than the return on investment. These results indicate a positive contribution associated with the reduction of potential environmental impacts and the reduction of energy inefficiencies on the economic profitability of the project. Therefore, it is recommended to implement improvements in the process through integration methodologies and waste utilization to obtain better indicators.

Also, Figure 5 presents the results of the sensitivity analysis carried out to evaluate the effect of the selected indicators on SWROIM. Three cases were considered: case 1 for the energy indicator $w_i = 1$, case 2 for the environmental indicator $w_i = 1$, and case 2 where $w_i = 1$ is considered for the safety indicator. The other indicators are considered as $w_i = 0.5$ in the three cases.

The results show that the environmental indicator is the most decisive in the sustainability evaluation. For case 2, the highest SWROIM value is obtained (92.88%), which indicates that optimal environmental conditions mostly favor the sustainable performance of the process; thus, strategies that favor the reduction of environmental impacts should be mainly applied. A case of biomass utilization was investigated to enhance investment decision-making by applying the sustainability metric within the Energy, Water, and Food nexus framework. The study yielded sustainability-weighted return on investment metrics (SWROIM) of 31%, 11%, 5%, and 12% for the production of Ammonia/Urea, methanol, liquid fuel, and an integrated biomass gasification combined cycle, as demonstrated by AlNouss *et al.*, (2019). Notably, these results were considerably lower than our current process.

In the context of methanol production from shale gas, a SWROIM of 70% was identified under conditions of 50 bar pressure and a recycling fraction of 0.9 (Guillén-Cuevas *et al.*, 2018a). The above highlights the necessity of employing distinct factors and weights to appropriately determine the optimal values for these influencing parameters (Guillén-Cuevas *et al.*, 2018b).

Conclusions

The inherent safety analysis and sustainability assessment of the dual crude palm and kernel oil production process was performed. The process was modeled under northern Colombian conditions for a production of 2.28 t/h and 0.57 t/h of crude palm oil and kernel oil, respectively. The results allowed us to conclude that the process is inherently safe. However, the main risks were identified in the drying and boiler stages due to the type of equipment used.

Table 5. Target indicators and the weighting factor for each technical parameter.

Aspect	Index	Units	Indicator indicator$_{target}$	w_i	
Safety	I_{TI}	Dimensionless	12	12	1
Energy	Exergy efficiency	%	18%	100%	1
Environmental	PEI output	PEI/h	2.60×10^{-4}	1.566×10^{-4}	1

Furthermore, the high inventory handled in the process is a stress factor for the equipment and compromises the overall safety of the process. Meanwhile no risk related to handling and interaction of the chemicals involved was identified. In terms of the sustainability evaluation, the process showed a SWROIM of 76.01%, which reveals that the considered indicators made a positive contribution to the return on investment. The environmental indicator was shown to be the most determinant over the SWROIM. General recommendations include monitoring the palm oil and almond drying units and the boiler and reducing the inventory handled in the whole process, besides implementing strategies that allow the reduction of energy inefficiencies and environmental impacts to ensure continuous development for the expansion of the palm sector in Colombia. Other indicators can be considered in the sustainability evaluation for future studies.

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Nomenclature and abbreviations

AP	Acidification Potential
ATP	Aquatic Toxicity Potential
$I_{INT,max}$	Chemical interaction subindex
I_{CI}	Chemical safety index
$I_{RM,max}$	Chemical reactivity subindex
$I_{COR,max}$	Corrosiveness subindex
$I_{(FL+Ex+TOX)\mathrm{max}}$	Dangerous substance index
Dow F& EI	Dow Fire and Explosion Index
$I_{EQ,max}$	Equipment safety subindex
$\dot{E}x_{destroyed}$	Exergy destroyed
η_{exergy}	Exergy efficiency
$\dot{E}x_{total,in}$	Total inlet exergy flow
GWP	Global Warming Potential
$HIRA$	Hazard Identification and Ranking
$HTPE$	Human Toxicity Potential by Inhalation Dermal Exposure
$HTPI$	Human Toxicity Potential by Ingestion
$ILUC$	Indirect land use change
ISI	Inherent Safety Index
I_I	Inventory subindex
$NuDIST$	Numerical Descriptive Inherent Safety Technique
ODP	Ozone Depletion Potential
$PCOP$	Photochemical Oxidation Potential
PAT	Profits after taxes
PEI	Potential Environment Impact
I_{PI}	Process inherent safety index
$I_{P,\mathrm{max}}$	Process pressure subindex
$I_{T,\mathrm{max}}$	Process temperature subindex
ROI	Return on Investment
$I_{ST,max}$	Safe Process Structure subindex
$SWHI$	Safety Weighted Hazard Index
$SWROIM$	Sustainable Weighted Return on Investment Metric
TCI	Total capital investment
I_{TI}	Total inherent safety index calculation
TTP	Terrestrial Toxicity Potential
WAR	Waste Reduction algorithm

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